

Topical Report:

NSTF Facilities Plan for Water-Cooled VHTR RCCS: Normal Operational Tests

Nuclear Engineering Division

About Argonne National Laboratory

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne, see www.anl.gov.

Availability of This Report

This report is available, at no cost, at <http://www.osti.gov/bridge>. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

Topical Report:
NSTF Facilities Plan for Water-Cooled VHTR RCCS:
Normal Operational Tests

by

M. T. Farmer, D. J. Kilsdonk, C. P. Tzanos, S. Lomperski, and R. W. Aeschlimann
Nuclear Engineering Division, Argonne National Laboratory

September 2006

work sponsored by

U. S. Department of Energy,
Office of Nuclear Energy, Science and Technology

TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	1
1.1 Background.....	1
1.2 Objectives and Approach.....	3
2.0 ORIGINAL NSTF DESIGN AND OPERATIONAL CAPABILITIES	4
2.1 Mission.....	4
2.2 Overall Facility Design.....	4
2.3 Instrumentation, Data Acquisition, and Control.....	7
2.4 Operational Capabilities.....	8
3.0 REQUIREMENTS FOR WATER-BASED RCCS TEST FACILITY	12
3.1 Scaling Approach.....	12
3.2 Data Needs for Code Validation.....	13
4.0 NSTF MODIFICATIONS TO SATISFY WATER-BASED RCCS DATA NEEDS	14
4.1 Overall Approach.....	14
4.2 Mechanical Modifications to Mock Up RCCS Flow Geometry.....	16
4.3 Heater Control System.....	22
4.4 Data Acquisition and Control	23
4.5 Instrumentation	24
5.0 COST AND SCHEDULE FOR FACILITY MODIFICATIONS	28
6.0 SUMMARY AND CONCLUSIONS	33
7.0 REFERENCES	34
APPENDIX A: NSTF FACILITY MODIFICATION PLAN FOR WATER-BASED RCCS	35

LIST OF FIGURES

	<u>Page</u>
1.1 Sketch of NSTF System Modifications for Water-Based RCCS Testing.....	2
2.1 Aerial View of the Building Housing NSTF	4
2.2 Schematic of GE PRISM RVACS Concept.....	4
2.3 Schematic Overview of NSTF	5
2.4 Cross-Section Through the Test Assembly.....	5
2.5 Heated Test Section Assemblies	7
2.6 Typical Heater Plate Assembly.....	7
2.7 Surface Temperature Thermocouple Installation.....	8
2.8 NSTF Surface Temperature and Heater Control Thermocouples on Heated Walls	10
2.9 NSTF Surface Temperature Thermocouples on Unheated Walls.....	11
4.1 Details of Water Standpipe Design.....	17
4.2 Key Design Features and Headering Approach for Standpipes.....	17
4.3 Cross Section of Test Assembly Showing Principal Details	18
4.4 Cavity Support Framework Modified for Variable Width Capability: (a) with heater plates in place, and (b) with plates removed for clarity.....	18
4.5 System Setup for Normal Mode Operational Tests	21
4.6 System Setup for Passive Mode Operational Tests	21
4.7 Heater Power Control System.....	23
4.8 Data Acquisition and Control Systems	24
4.9 Center Standpipe Instrumentation Layout	25

LIST OF TABLES

	<u>Page</u>
2.1 Original NSTF Design and Operating Parameters.....	6
2.2 Summary of NSTF Instrumentation Approach.....	9
3.1 Characteristics of Prototype Water-Based RCCS and Scaled Experiment.....	13
3.2 Summary of NSTF Requirements to Provide Code Validation Data	13
4.1 Approach for Satisfying Water-Based RCCS Data Needs	15
4.2 NSTF Instrumentation Summary for Water-Based RCCS Testing	27
5.1 Schedule for Completion of Key Tasks	29
5.2 Estimated Costs for the Proposed Workscope	31

1.0 INTRODUCTION

1.1 Background

As part of the Department of Energy (DOE) Generation IV roadmapping activity, the gas-cooled Very High Temperature Reactor (VHTR) has been selected as the principal concept for hydrogen production and other process-heat applications such as district heating and potable water production. On this basis, the DOE has selected the VHTR for additional R&D with the ultimate goal of demonstrating emission-free electricity and hydrogen production with this advanced reactor concept.

One of the key passive safety features of the VHTR is the potential for decay heat removal by a combination of natural convection and radiation across an interstitial air gap that separates the reactor vessel from either air-filled tubes or water-filled pipes. For either coolant, sufficient natural convection flow is calculated to develop through the tubes to keep fuel temperatures at acceptably low levels. Both the air- and water-cooled Reactor Cavity Cooling System (RCCS) designs contain many features that are similar to the Reactor Vessel Auxiliary Cooling System (RVACS) that was developed for the General Electric PRISM sodium-cooled fast reactor. As part of the DOE R&D program that supported the development of this fast reactor concept, the Natural Convection Shutdown Heat Removal Test Facility (NSTF) was developed at ANL to provide proof-of-concept data for the RVACS under prototypic natural convection flow, temperature, and heat flux conditions. Due to similarities between RVACS and the RCCS, current VHTR R&D plans call for the utilization of the NSTF to provide RCCS model development and validation data, in addition to supporting design validation and optimization activities.

In support of this effort, ANL has been tasked with the development of engineering plans for mechanical and instrumentation modifications to NSTF to ensure that sufficiently detailed temperature, heat flux, velocity and turbulence profiles are obtained to adequately qualify the codes under the expected RCCS operational ranges. Since an actual plant design (or vendor) has not yet been selected, both air- and water-based system designs have been considered as part of the planning process. Work last year addressed the air-based system,¹ while the work documented in this report addresses the water-based system. Supporting scaling and scoping cavity analysis activities² for the RCCS carried out in parallel with this experiment planning task, in addition to results available in the open literature, indicate that: (a) strong 3-D effects result in large heat flux, temperature, and heat transfer variations around the standpipe wall; (b) there are large differences in the heat transfer coefficients predicted by turbulence models and heat transfer correlations, and this underscores the need of experimental work to validate the thermal performance of the RCCS; (c) there are complicated two phase flow issues (i.e., steam flashing in the upper regions of the test section, and the possibility of nucleate boiling in the heated section) that complicate the system analysis; and (d) scaled tests at the NSTF would embody all important fluid flow and heat transfer phenomena in the RCCS, in addition to covering the entire parameter ranges that characterize these phenomena. Details will be confirmed in follow-on facility CFD and system-level code analyses.

Although a specific design has not yet been selected for the VHTR, the PBMR water-based RCCS is used as a planning basis for the purposes of this study since that design is mature enough that an appropriately scaled experiment design can be developed. A schematic that illustrates key attributes of the experiment concept that has been developed to study the PBMR RCCS is shown in Figure 1.1. This system contains the same physical elements as the prototype, plus additional equipment to facilitate data gathering to support code validation testing. In particular, the prototype consists of a series of oval standpipes surrounding the reactor vessel to provide cooling of the reactor cavity during both normal and off-normal operating conditions. The standpipes are headered (in groups of four in the prototype) to water supply (header) tanks that are situated well above the reactor vessel to facilitate natural convection cooling during loss of forced flow sequences. During normal operations, the water is pumped from a heat sink located outside the containment to the headered inlets to the standpipes. The water is then delivered to each standpipe through a centrally located downcomer that passes the coolant to the bottom of each pipe. The water then turns 180° and rises up through the annular gap while extracting heat from the reactor cavity due to a combination of natural convection and radiation across the gap between the reactor vessel and standpipes. The water exits the standpipes at the top where it is headered (again in groups of four) into a return line that passes the coolant to the top of the header tank. Coolant is drawn from each tank through a fitting located near the top of the tank where it flows to the heat rejection system located outside the containment. This completes the flow circuit for normal operations.

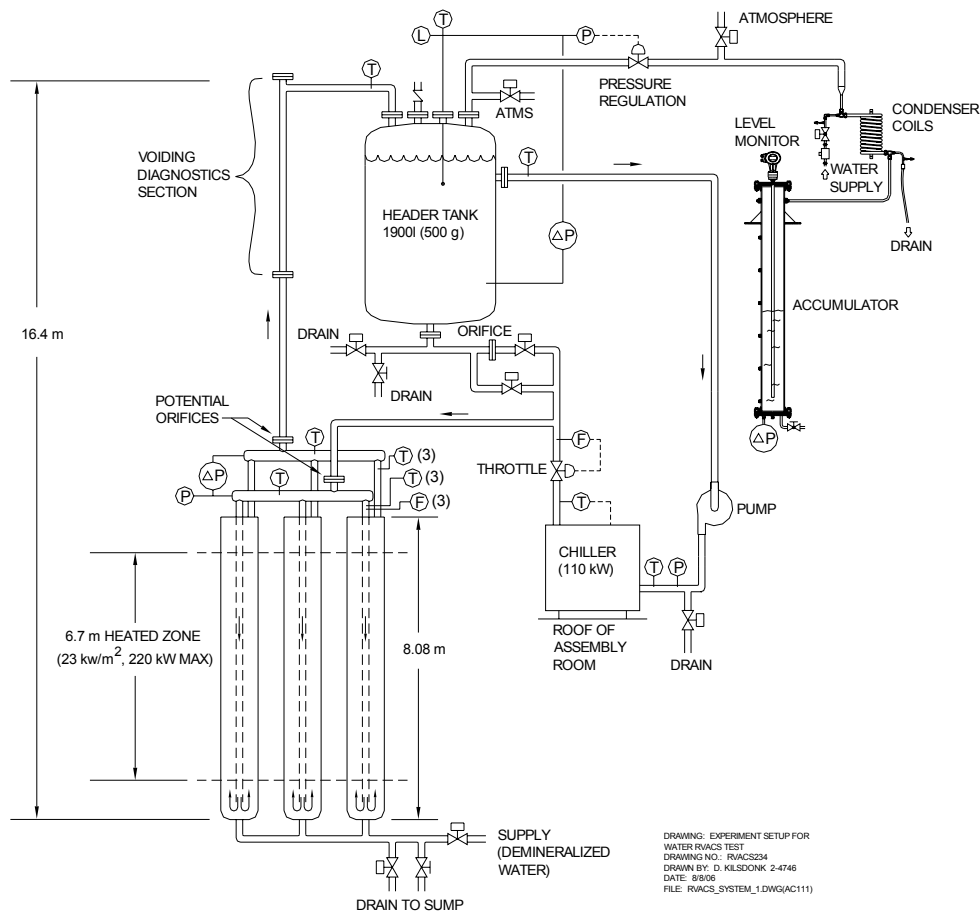


Figure 1.1. Sketch of NSTF System Modifications for Water-Based RCCS Testing.

During off-normal conditions, forced convection water cooling in the RCCS is presumed to be lost, as well as the ultimate heat sink outside the containment. In this case, water is passively drawn from an open line located at the bottom of the header tank. This line is orificed so that flow bypass during normal operations is small, yet the line is large enough to provide adequate flow during passive operations to remove decay heat while maintaining acceptably low fuel temperatures. In the passive operating mode, water flows by natural convection from the bottom of the supply tank to the standpipes, and returns through the normal pathway to the top of the tanks. After the water reaches saturation and boiling commences, steam will pass through the top of the tanks and be vented to the atmosphere. In the experiment system shown in Figure 1.1, a steam condensation and collection system is included to quantify the boiling rate, thereby providing additional validation data. This steam condensation system does not exist in the prototype.

1.2 Objectives and Approach

The purpose of this work is to develop a high-level engineering plan for mechanical and instrumentation modifications to NSTF in order to meet the following two technical objectives related to the water-based RCCS design:

1. provide CFD and system-level code development and validation data for the water-based RCCS under properly scaled conditions for both normal and off-normal (i.e., passive) operating conditions, and
2. support RCCS design validation and optimization.

As background for this work, the report begins by providing a summary of the original NSTF design and operational capabilities. Since the facility has not been actively utilized since the early 1990's, the next step was to assess the current facility status; and this step was completed as part of last year's workscope.¹ (The assessment indicated that the facility is in sound mechanical shape; refer to Reference 1 for details.) With this background material in place, the data needs and requirements for the water-based RCCS facility are then defined on the basis of the supporting scaling analysis.² With the high-level requirements for the facility so established, appropriate mechanical and instrumentation modifications to NSTF are then developed in order to meet the overall project objectives. A cost and schedule for modifying the facility to satisfy the RCCS data needs is then provided.

2.0 ORIGINAL NSTF DESIGN AND OPERATIONAL CAPABILITIES

2.1 Mission

The Natural Convection Shutdown Heat Removal Test Facility (NSTF) is a large-scale test facility located in Bldg. 310 on the Argonne National Laboratory site. An overview photograph of the building where the facility is located is shown in Figure 2.1. The facility was originally developed to provide confirmatory data for the GE PRISM RVACS design. A schematic diagram showing key elements of the PRISM RVACS is provided in Figure 2.2. The NSTF mocked up the air-flow path formed by the reactor guard vessel (heated wall) and the outer duct wall surrounding the guard vessel.

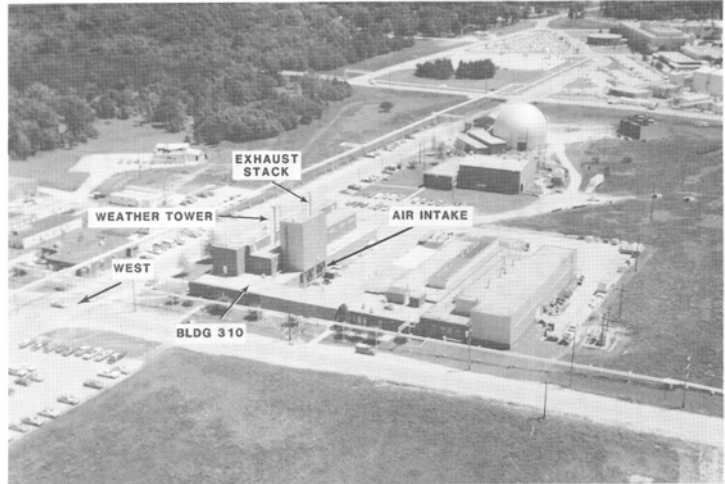


Figure 2.1. Aerial View of the Building Housing NSTF.

2.2 Overall Facility Design

Principal components of the facility consisted of the structural module, electric heaters, instrumentation, insulation, and a computerized data acquisition and control system. A schematic overview of the facility that illustrates key components is provided in Figure 2.3, while a summary of facility design and operating parameters is provided in Table 2.1.

As is evident from Figure 2.3, the key features of the structural module consisted of an inlet plenum, a heated zone that mocked up the exterior of the reactor guard vessel, and an unheated stack or chimney. All sections, with the exception of the inlet plenum, were thermally insulated to minimize parasitic

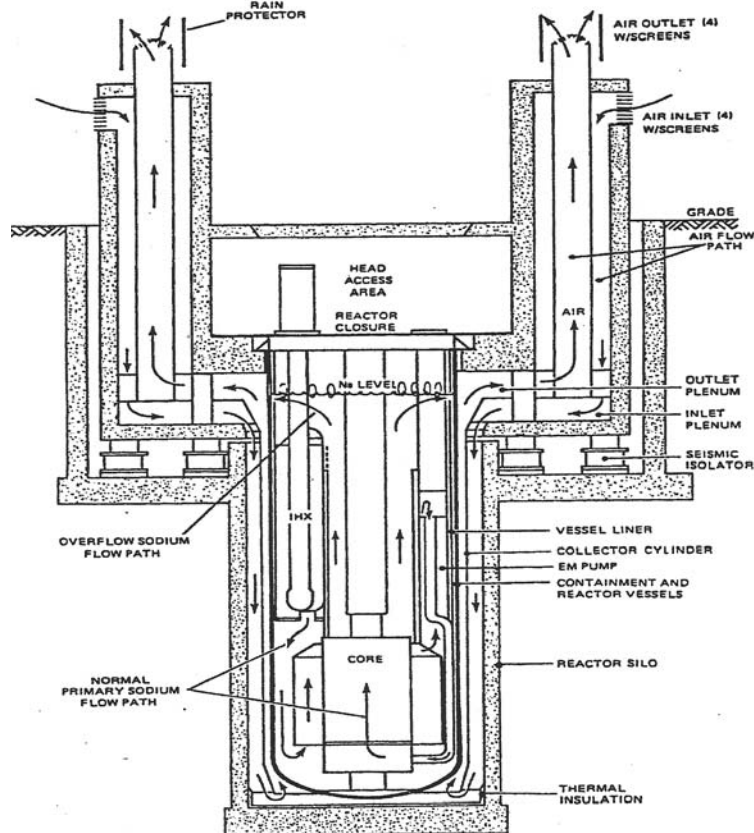


Figure 2.2. Schematic of GE PRISM RVACS Concept.

heat losses to the environment. The heated channel breadth was 1.32 m. As originally designed, the channel width could be adjusted anywhere from 30.4 cm to 45.6 cm. A cross-section through the heated section of the structure is provided in Figure 2.4. The surfaces that simulate the guard vessel wall (heated wall) and the outer duct wall were smooth, 2.54 cm thick carbon steel plates. Within the heated zone, fins or ribs could be installed on the inner walls of the air channel to enhance turbulence and heat transfer. A photograph showing the heated test section walls during installation is provided in Figure 2.5. Note that there is sufficient space within the high bay where the facility is located to increase the channel width to as much as 150 cm if the need arises. However, this would require modification of the mechanical framework that supports the heated and unheated walls that simulate the guard vessel and outer duct wall. In addition, transition ductwork would need to be provided to mate the modified heated section to the existing stack.

In terms of simulating the thermal boundary conditions on the outside surface of the PRISM reactor guard vessel, the facility was capable of operation in one of two thermal modes: (1) constant (uniform) guard vessel wall temperature at up to 677 °C, or (2) constant (uniform) heat flux at levels ranging up to 21.5 kW/m². Alternatively, step-wise variation of these two boundary conditions was possible, either singly, or in any arbitrary combination. A total of 10

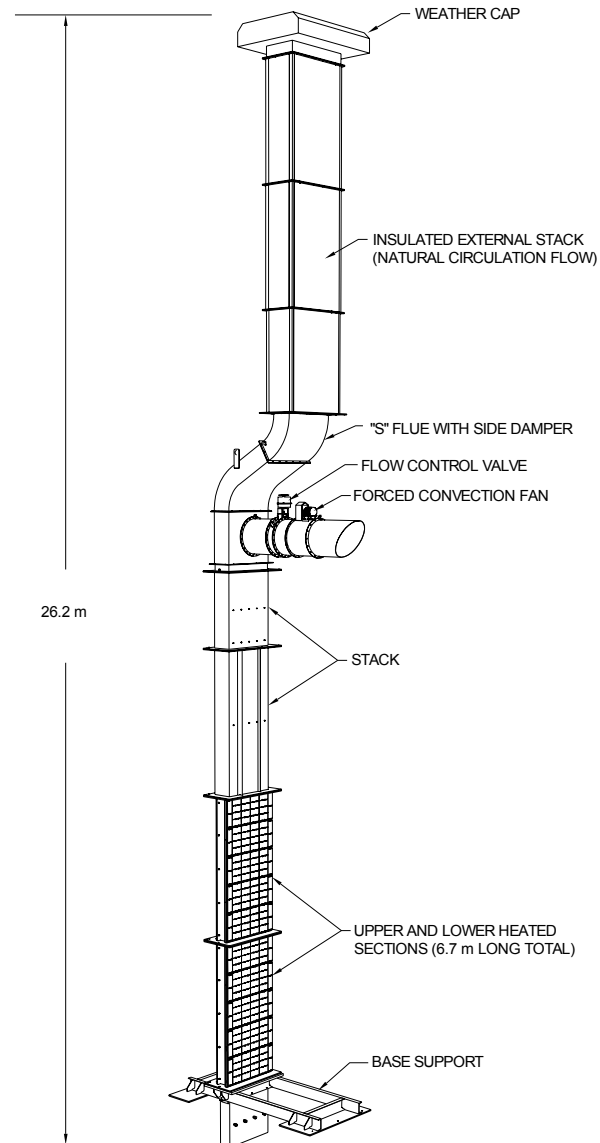


Figure 2.3. Schematic Overview of NSTF.

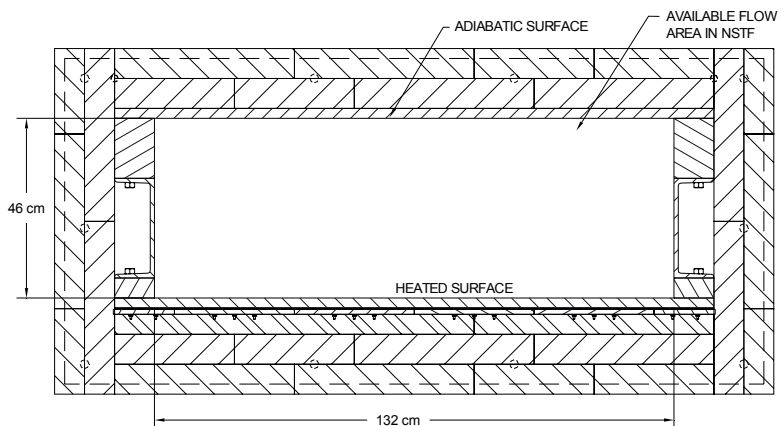


Figure 2.4. Cross-Section Through the Test Assembly.

Table 2.1. Original NSTF Design and Operating Parameters.

Parameter	Value	Notes
General	Natural convection air-flow T-H test facility	The case of water-cooled RCCS standpipes can be readily addressed in the facility
Overall Facility Height	26.2 m (86 ft.)	-
Flow operating modes	Natural or forced convection	Facility includes fan loft
Heated Section Flow Area	Rectangular, 46 cm x 132 cm	Expandable to 150+ cm x 132 cm
Heated Section Length	6.7 m	-
Heating Distribution	One long side heated; other 3 sides adiabatic	-
Heated Section Operating Modes	1. Constant heat flux (limit: 21.5 kW/m ²) 2. Constant temperature (limit: 677 °C) 3. Arbitrary combination of 1 & 2	Heater limits: 23.7 kW/ m ² and 1200°C. Structure strength/thermal expansion tolerances are being re-examined for possible higher temperature operation.
Total Input Power	220 kW	-
Resolution of Axial Heat Flux/Temperature Control	10-67 cm axial segments	Resolution can be reduced to as little as 16 cm axial increments
Inlet Section Area	Rectangular, 46 cm x 132 cm	Expandable to 150+ cm x 132 cm
Inlet Section Length	1.5 m	-
Chimney Height	18.0 m	-
Chimney Area	Rectangular, 46 cm x 132 cm	-

heater zones spanned the 6.7 m heated length of the NSTF; each bank was independently controlled. Thus, the axial resolution in heat flux and/or temperature control corresponded to 67 cm.

The heat input to the guard vessel was provided by an assembly of ceramic electrical heaters that were fastened to 3.2 mm thick stainless steel mounting plates. Heat was transferred through the plates and then conducted across a small gap to the guard vessel surface. Power to the heaters was feedback-controlled based on readings from thermocouples attached to the surface between the mounting plate and the heaters. A photograph showing a heater mounting plate prior to installation on the test section is provided in Figure 2.6. As shown in Table 2.1, the total input power that could be provided by the 10 banks of plate heaters was 220 kW.

Above the heated zone the flow channel expanded to a cross section of 1.32 m by 45.6 cm. Two flow paths were provided. The main path for the experiments was upward through an “S” curve and then vertically through the building roof. This provided a stack for natural convection measuring nearly 15.2 m in vertical length. As shown in Figures 2.1 and 2.3, the top of the stack extended 6.1 m above the roof. The second flow path consisted of a fan with a variable motor speed and a damper. This feature was provided for forced convection tests, when a controlled air flow rate was desired.

2.3 Instrumentation, Data Acquisition, and Control

The data acquisition system (DAS) for the original system was capable of sampling 300 channels. The large majority of these instruments consisted of

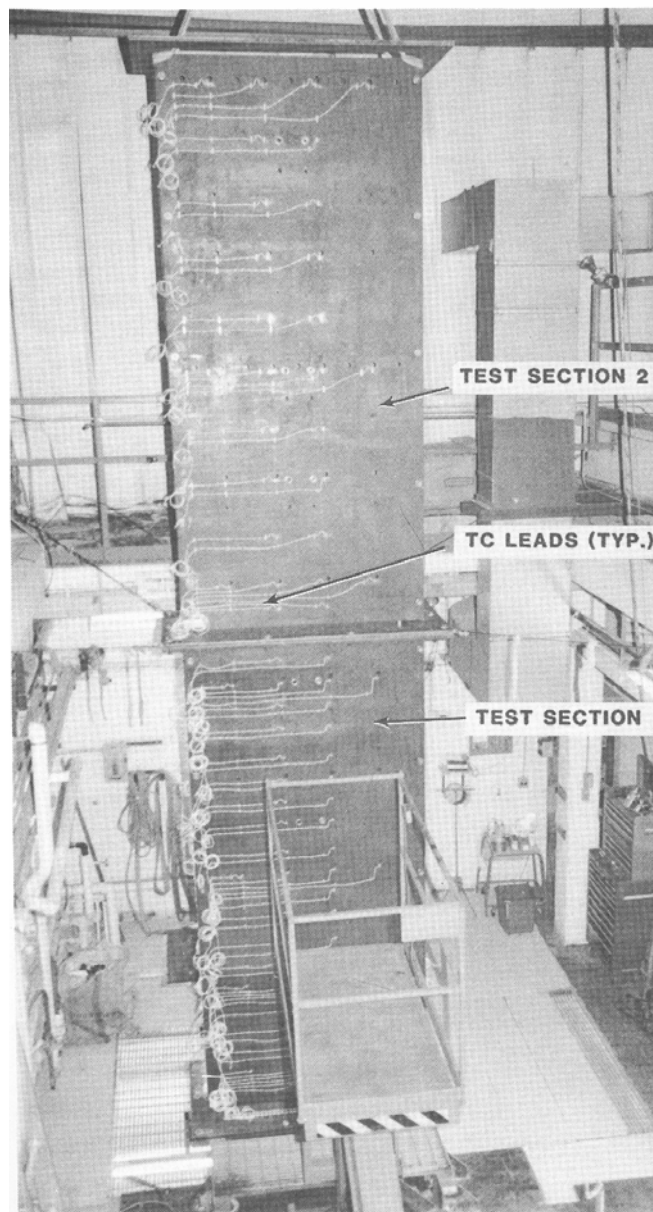


Figure 2.5. Heated Test Section Assemblies.



Figure 2.6. Typical Heater Plate Assembly.

thermocouples that were dedicated to monitoring temperatures in the heated zone of the assembly. The DAS stored the data on disk; selected channels were displayed at the operator's console to help guide test operations. The DAS computer was also used to compute system parameters for real-time display. As discussed in Section 4, the heater power control and DAS systems will be completely renovated as part of the current work to satisfy the RCCS data needs.

The NSTF was heavily instrumented to help guide experiment operations, and also evaluate the heat removal performance for particular configurations under both natural convection and forced flow conditions. A summary of the overall instrumentation approach is provided in Table 2.2. As shown in the table, instruments were provided to measure local surface temperatures, local bulk air temperatures, local and bulk air velocities, air volumetric and mass flow rates, total normal radiation heat flux, and electrical power supplied to the duct wall heaters. The instrumentation consisted of thermocouples, pitot-static traversing probes, a pitot-static air flow rake, differential pressure transducers, radiation flux transducers, anemometers, and air pressure and humidity gages. The primary measurement objective was to determine the local heat fluxes and the associated heat transfer coefficients, as well as the bulk (or integral) heat removal rate of the system. To achieve this objective, both the heated and unheated walls of the facility were heavily instrumented with flush-mount thermocouples for accurate measurement of surface temperature profiles while not disrupting the flow field. A drawing that illustrates the surface thermocouple installation technique is provided in Figure 2.7, while schematics that show all thermocouple locations on the heated and unheated walls of the facility are provided in Figures 2.8 and 2.9, respectively.

2.4 Operational Capabilities

The various facility operating approaches and limitations have already been summarized as part of the overall facility description (e.g., see Table 2.1). During testing at NSTF in support of the GE PRISM RVACS design, flow velocity and temperature measurements were made for both smooth and finned channel walls. In addition, some measurements were made with a blocked flow channel configuration. Operationally, these measurements covered a range of natural convection flow conditions at Reynolds numbers above 40,000. Thus, this data is not directly applicable to the VHTR air RCCS, since the Reynolds number range for this system is not expected to exceed 20,000.³

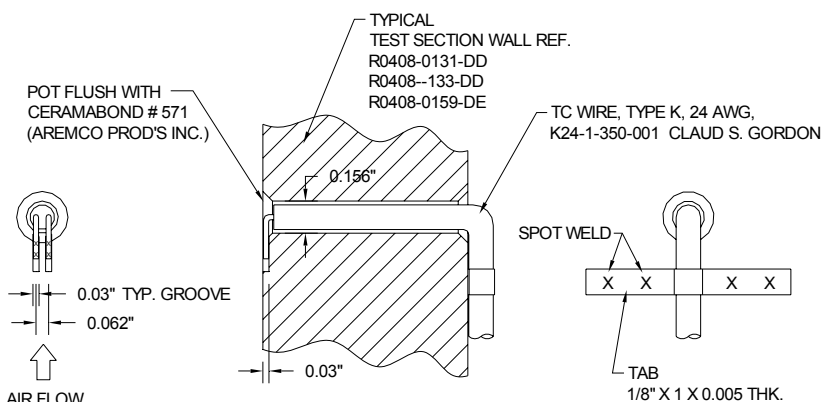


Figure 2.7. Surface Temperature Thermocouple Installation.

Table 2.2. Summary of NSTF Instrumentation Approach.

Measurement	Instrument	Purpose/Location
Temperature	Thermocouples	<ol style="list-style-type: none">1. Heater Over-temperature/control2. Guard vessel wall: ~ 60 on lower section at ~ 25 cm axial intervals, ~ 44 on upper section at ~ 50 cm intervals.3. Duct wall: ~ 48 on lower section at ~ 25 cm axial intervals, ~28 on upper section at ~ 50 cm intervals.4. Side walls: ~ 50 cm intervals.5. Heated section inlet: 4 radiation-shielded6. Heated section exit: 4 radiation-shielded
Flow velocity distributions	Pitot-static, anemometer, rotameter	<ol style="list-style-type: none">1. Fixed pitot-static rakes at heated section inlet and exit (4 transverse locations each).2. Access ports for movable pitot-static tubes and/or anemometers at 1.2 m axial increments; 4 transverse access ports at each axial elevation.3. Rotameter for air velocity/direction measurement at stack exit.
Pressure	Strain-gauge transducers	<ol style="list-style-type: none">1. Inlet static2. Test section differentials
Radiation heat flux	Radiation sensor	Four used in NSTF; can be placed in selected access ports at 1.2 m axial increments; 4 transverse access ports at each axial elevation
Surface emissivity	Radiation sensor	"
Heater AC Power Distribution	Voltmeter and Halltipliers	Measure axial power distribution at 10 axial elevations

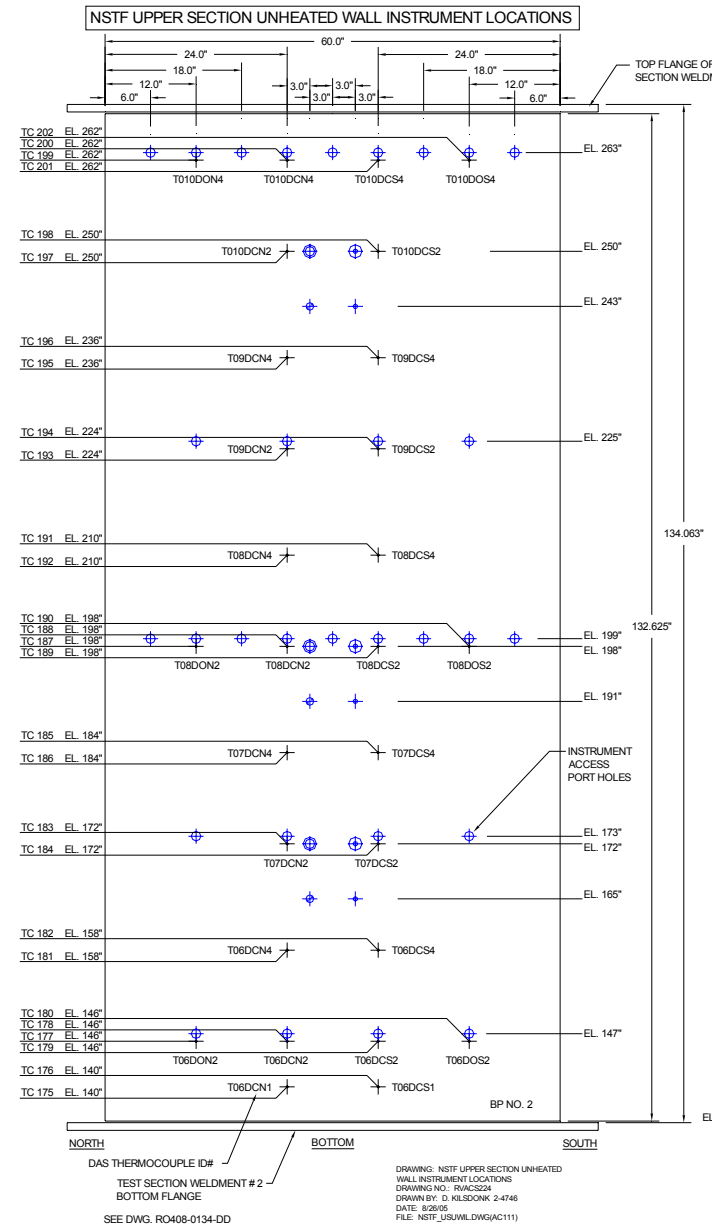
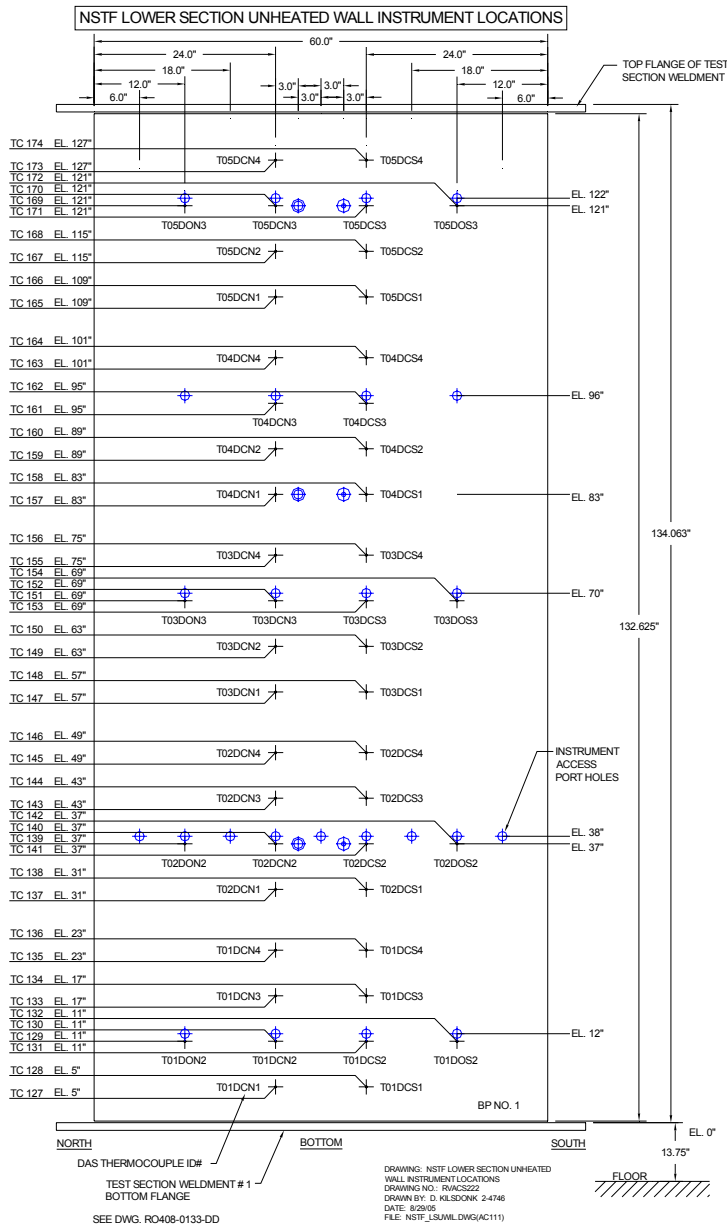


Figure 2.9. NSTF Surface Temperature Thermocouples on Unheated Walls.

3.0 REQUIREMENTS FOR WATER-BASED RCCS TEST FACILITY

Supporting scaling studies have been carried out by Tzanos² to provide the technical basis for identifying the appropriate scale and required mechanical and instrumentation modifications to NSTF to meet key water-based RCCS data needs. The principal findings from this work² that directly impact the facility planning process are summarized below.

3.1 Scaling Approach

As noted previously, although a specific design has not yet been selected for the VHTR, the PBMR water-based RCCS is used as a planning basis for the purposes of this study since that design is mature enough that an appropriately scaled experiment can be developed. Approximate characteristics of this system are summarized in Table 3.1, while generic system features were shown previously in Figure 1.1. The prototype consists of a series of oval standpipes surrounding the reactor vessel to provide cooling of the reactor cavity during both normal and off-normal operating conditions. The standpipes are headered in groups of four to water supply tanks that are situated well above the reactor vessel to facilitate natural convection cooling during loss of forced flow sequences. During normal operations, the water is pumped through a closed circuit that includes the standpipes that extract heat from the reactor cavity, and dump the heat in a sink that is located outside the containment. The oval standpipes are roughly 25 cm x 50 cm, and are in the range of 20 m high. The overall height of the system (defined as the distance from the bottom of the standpipes to the top of the header tanks) is ~ 40 m.

During off-normal (passive) system operations, forced convection water cooling in the RCCS is lost. In this case, water is passively drawn from an open line located at the bottom of each header tank. Again, the particulars are design-dependent, but for the PBMR system this line is orificed so that flow bypass during normal operations is small, yet the line is large enough to provide adequate flow during passive operations to remove decay heat while maintaining acceptably low fuel temperatures. In the passive operating mode, water flows by natural convection from the supply tank to the standpipes, and returns through the normal pathway to the top of the tanks. After the water reaches saturation and boiling commences, steam will pass through the top of the tanks and vent to the atmosphere.

The system described above defines the key physical elements to be included within the test facility so that system behavior during both normal and passive operational modes can be reasonably simulated. As described in the next section, NSTF can accommodate up to three water standpipes with full scale cross-section. For systems that rely on natural convection, similitude between the experiment and prototype can rarely be achieved unless the scale of the experiment is selected to match the prototype. On this basis, the cross-sectional scale of the experiment is selected to be nominally 1:1 with respect to the PBMR system. Given the overall available height within the NSTF high bay of ~ 16 m, then the vertical scaling of the facility is selected to be ~ 1/2. As deduced through the scaling analysis,² a system that is full scale in cross section and 1/2 scale vertically can best achieve similitude with the prototype if the heat flux delivered to the standpipes is ~ 40 % in excess of the prototype. Thus, this is the approach that is adopted for the NSTF water-based RCCS experiment design; namely, fabricate a full-scale

cross-section, $\frac{1}{2}$ scale vertical facility that reasonably replicates the overall physical structure of the prototype RCCS. Overall system characteristics are summarized in Table 3.1.

Table 3.1. Characteristics of Prototype Water-Based RCCS and Scaled Experiment.

Parameter	Prototype	NSTF Scaled Model
Total number of water standpipes	~ 70	3
Number of standpipes per header tank	~ 4	3
Standpipe cross sectional area	~ 25 x 50 cm	same
Standpipe Length	~20 m	8.1 m
Total elevation difference between header tank and standpipes	~ 40 m	16.1 m
Facility scale	N/A	1:1 radially, $\sim\frac{1}{2}$ vertically
Vessel wall peak heat flux during normal/off normal conditions	3 - 5 kW/m ²	1.4•prototype for similitude (heater capability: 21 kW/m ²)
Vessel wall peak temperature	~350 °C	Same (heater limit: 1200°C)
Standpipe boil-down time at peak heat flux without makeup water	~70 hours	Properly scaled

3.2 Data Needs for Code Validation

Based on the above discussion as well as the supporting scaling study,² high level experiment design requirements for the NSTF were established. These requirements are summarized in Table 3.2. The first requirement is to mock up the actual geometry of the RCCS to the greatest extent possible given the physical constraints of the facility. The approach by which this requirement is addressed has just been described. The remaining four requirements are data-related. Namely, measurements of the axial and radial temperature and heat flux distributions on the standpipe walls are required. In addition, data on the standpipe interior water temperature distributions are needed. This collection of measurements will provide the necessary data to evaluate heat transfer coefficients not only axially along the standpipe length, but also radially around the extent of the pipe walls. Finally, void fraction measurements are needed in the return piping from the standpipes to the header tank in order to characterize performance during passive system operations for system-level code validation purposes.

This information forms the basis for the facility modification plan that is provided in the next section.

Table 3.2. Summary of NSTF Requirements to Provide Code Validation Data.

No.	Requirement
1	Mock-up water RCCS geometry under properly scaled flow conditions for both normal and passive operational modes
2	Obtain data on the water, standpipe, and cavity axial temperature distributions under properly scaled flow conditions.
3	Obtain data on the standpipe heat flux distributions under properly scaled flow conditions.
4	Obtain data on the cavity bulk gas velocity and temperature distributions.
5	Obtain data on voiding in the return piping from the standpipes to the header tanks

4.0 NSTF MODIFICATIONS TO SATISFY WATER-BASED RCCS DATA NEEDS

Overall code validation data needs for the water-based RCCS were described in the previous section. The objective of this section is to outline a high-level plan for modifying NSTF to meet these data needs.

4.1 Overall Approach

A summary of the experiment approach for satisfying key data needs is provided in Table 4.1. The first requirement is to mock up the actual geometry of the water-based RCCS under properly scaled flow conditions for both normal and passive operational modes. To meet this requirement, the approach is to strive for similitude between the experiment and prototype to the greatest extent possible. Given the prototype dimensions, as well as the physical characteristics of the NSTF, the results of the scaling analyses² indicate that similitude can best be achieved when the cross-sectional scale of the experiment is selected to be nominally 1:1, while the vertical scale is selected to be $\sim 1/2$. Under these conditions, the analyses² further indicate that for the passive operational mode, properly scaled data can be obtained if the heat flux delivered to the standpipes is $\sim 40\%$ in excess of the prototype. Thus, this is the approach that is adopted for the NSTF water-based RCCS experiment design that is intended to investigate passive system operations; namely, fabricate a full-scale cross-section, $1/2$ scale vertical facility that reasonably replicates the overall physical structure of the prototype (PBMR) RCCS. Overall system characteristics were previously summarized in Table 3.1. As the table indicates, NSTF has significant margin (i.e., a factor of 3) with respect to the power requirements for conducting this type of natural convection testing.

For the normal operational tests, the experiment approach is to use essentially the same system described above for the passive operational tests. However, the facility will be further equipped with a pump and appropriate flow paths to establish and maintain properly scaled water flow rates through the system. Furthermore, a suitable heat sink will be provided, so that steady state conditions can be established and maintained. Finally, appropriate instrumentation will be provided to characterize the system overall thermalhydraulic performance. As noted above, the vertical scale of the facility is nominally $1/2$ with respect to the prototype. Thus, if tests are needed in which the water mass flux through the pipes matches the prototype, then the surface heat flux may need to be increased by a factor of two to match the temperature rise across the system. As shown in Table 3.1, NSTF has more than sufficient margin in heating power to meet the requirements if this type of testing is needed.

As indicated in Table 4.1, the four remaining requirements for water-based RCCS testing are data-related. Namely, measurements of the water, standpipe, and cavity axial temperature distributions are required, in addition to the standpipe surface heat flux distributions. The approach for obtaining this information is to highly instrument the center standpipe to measure the water and standpipe internal and external surfaces temperatures at a minimum of 6 axial positions along the heated length. Heat flux meters will also be co-located at the surface temperature measurement locations to provide heat flux data. This collection of measurements will provide the information needed to evaluate heat transfer coefficients from the coolant to the standpipe walls at various axial and radial positions.

Table 4.1. Approach for Satisfying Water-Based RCCS Data Needs.

No.	Requirement	Approach	Notes
1	Mock-up water RCCS geometry under properly scaled flow conditions	Three (3) 8.1 m long standpipes with prototypic cross-section installed in heated section of NSTF. Peripheral area around standpipes sealed at top and bottom to achieve prototypic flow geometry. Apply prototypic surface temperature and/or heat flux boundary conditions to achieve prototypic flow patterns.	Standpipe dimensions based on an existing design, but other designs can be accommodated.
2	Obtain data on the water, standpipe, and cavity axial temperature distributions under properly scaled flow conditions.	Highly instrument the center standpipe to measure the water and standpipe internal and external surfaces temperatures at a minimum of 6 axial positions along the heated length. Also obtain surface temperature measurements on both the heated and unheated cavity walls.	1. Key information for CFD code validation under prototypic VHTR water RCCS flow conditions. 2. Data from 2-4 provides information needed to evaluate heat transfer coefficients vs. axial position within the standpipes.
3	Obtain data on the standpipe heat flux distributions under properly scaled flow conditions.	Instrument both radially and axially the center standpipe with heat flux meters to provide direct measurements of the heat flux distributions around the pipe at a minimum of 6 axial elevations.	
4	Obtain data on the cavity bulk gas velocity and temperature distributions.	Utilize insertable hot wire anemometers (back-up: pitot tubes) with co-located, radiation-shielded, thermocouples to measure bulk gas velocity and gas temperature distributions at ~ 1 meter axial increments.	
5	Obtain data on voiding in the return piping from the standpipes to the header tanks	Instrument pipe sections with differential pressure transducers to determine the void fraction as a function of position.	-

Other data relevant to characterizing the heat transfer on the air-side of the cavity are required. In particular, surface temperature measurements will be obtained on both the heated and unheated cavity walls, in addition to the cavity bulk gas velocity and temperature distributions. This data, in conjunction with the heat flux measurements, will provide the necessary information for evaluating bulk heat transfer coefficients on the air side of the pipes.

In addition to the data that focuses on evaluating the heat transfer characteristics inside the cavity, other measurements will be obtained to evaluate system operational characteristics and assess overall performance. For the passive operating mode, data will be obtained on the nature and extent of coolant voiding in the return piping from the standpipes to the header tanks using standard measurement techniques. For the normal operating mode, instruments will be provided to check system energy balances and to characterize overall thermalhydraulic performance.

Additional details regarding the experiment approach for satisfying RCCS data needs are provided in the balance of this section.

4.2 Mechanical Modifications to Mock Up RCCS Flow Geometry

As shown in Figure 2.3, NSTF was originally designed as a large air draft test facility for investigating the GE PRISM RVACS operational performance. The overall approach for modifying this facility for water-based RCCS testing will be to modify the heated test section portion of the facility to accommodate the water standpipes, and use the balance of the large high bay area to incorporate mockups of the balance of the system, including the header tank, chiller, and interconnecting piping. Thus, the first step in the facility modifications will be the removal and storage of the ductwork above the two heated test section components (see Figure 2.3), thereby providing direct access to the heated sections, and also providing open space above these structures for the balance of the system components.

As discussed in Section 4.1, the overall approach for mocking up the water-based RCCS is to try to match the prototype geometry to the greatest extent possible given the facility size constraints. This is accomplished by installing three water standpipes of prototypic cross-section, wall thickness, and pitch in the heated section of NSTF. The standpipe fabrication details are shown in Figure 4.1, while the pipe mounting and headering approaches are illustrated in plan view in Figures 4.2 and 4.3. The overall tube length is 8.1 m, which provides sufficient length to mechanically attach the standpipes at the top of the heated portion of the facility, pass through the entire 6.7 m long heated test section length, and penetrate through the bottom of the base support weldment with sufficient clearance to mechanically support the pipes and provide feed throughs for instrumentation mounted within the center, highly instrumented standpipe. Additional details regarding system instrumentation are provided later in this section.

The second step in the rework of the facility for water-based testing will be the modification of the test section base weldment and cavity wall support framework to allow the cavity width to be adjusted from the current maximum value of 45.7 cm (18 inch; see Table 2.1) up to 102.9 cm (40.5 inch) in increments of 7.62 cm (3.0 inch). This modification will allow the overall physical characteristics of the PBMR RCCS to be reasonably mocked up at the largest cavity opening size of 102.9 cm, while providing flexibility to accommodate other RCCS air- or

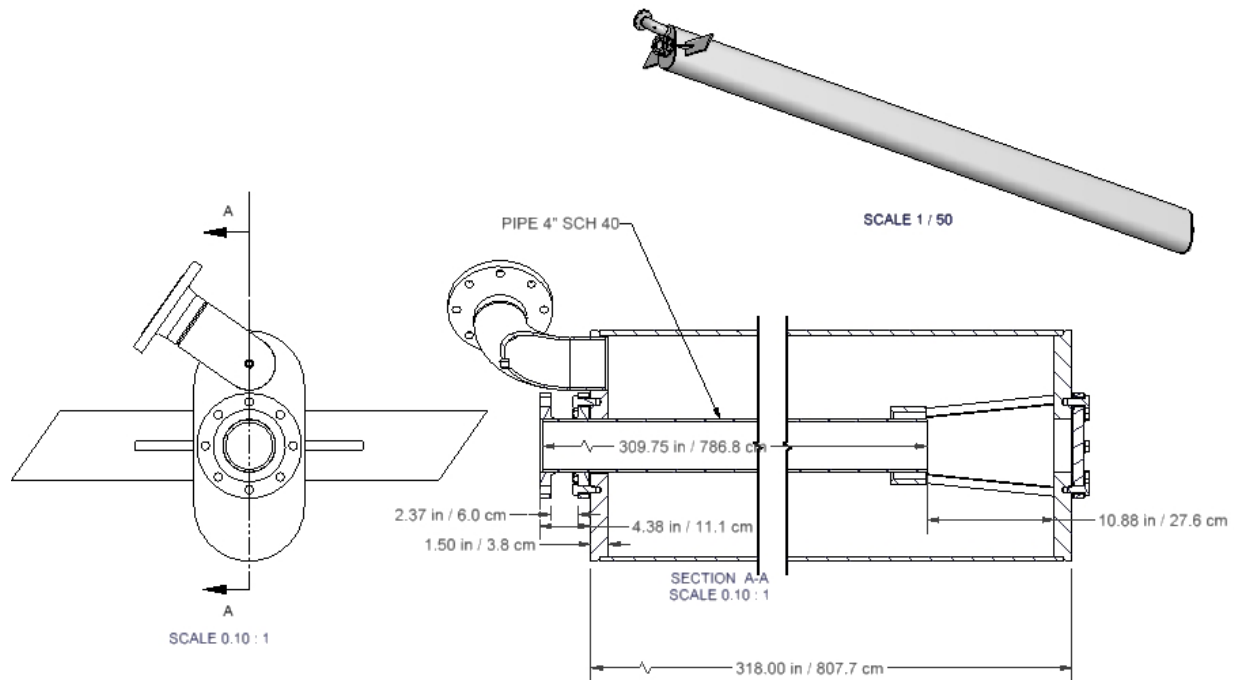


Figure 4.1. Details of Water Standpipe Design.

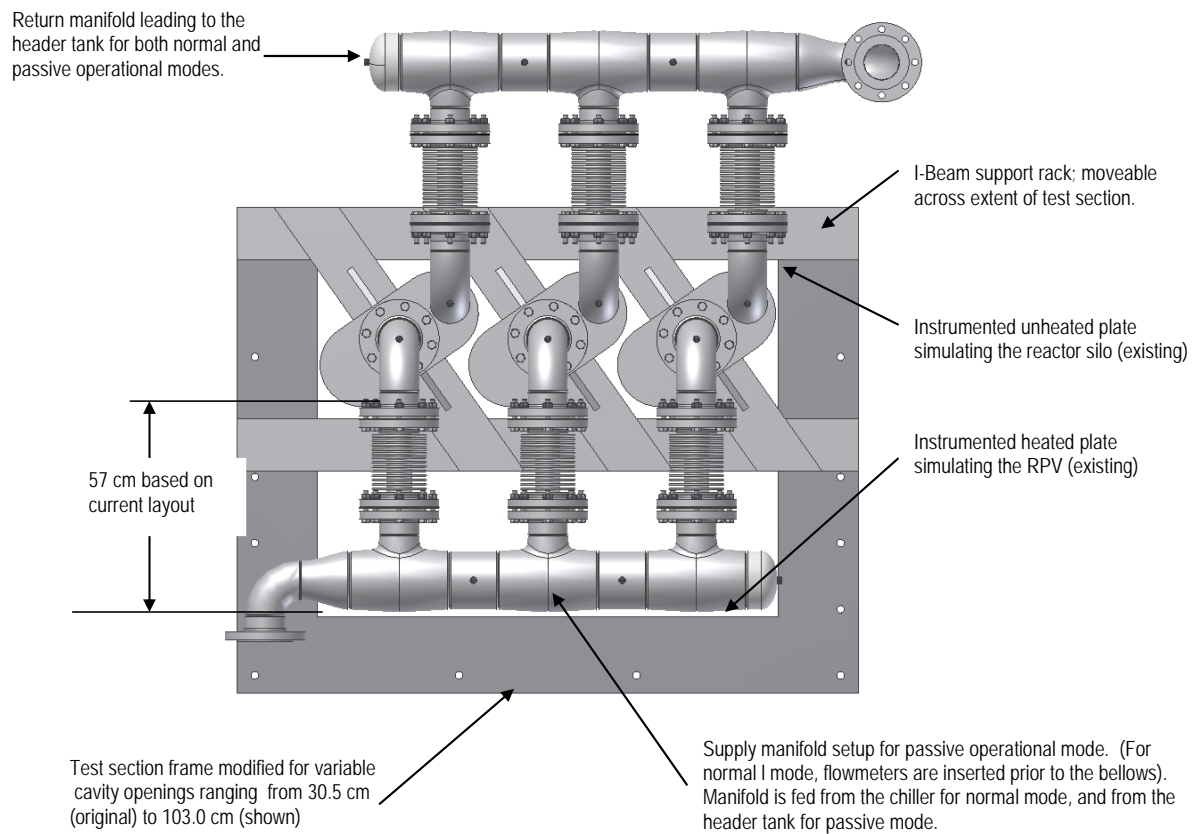


Figure 4.2. Key Design Features and Headering Approach for Standpipes.

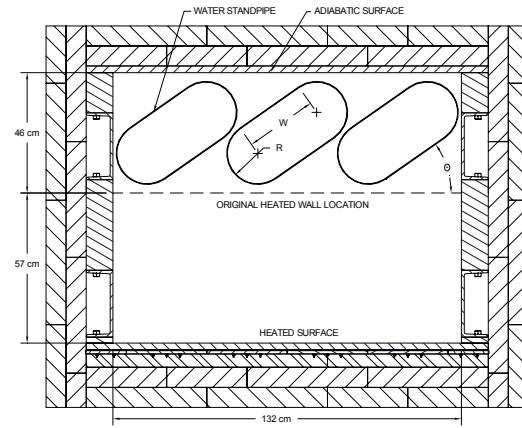
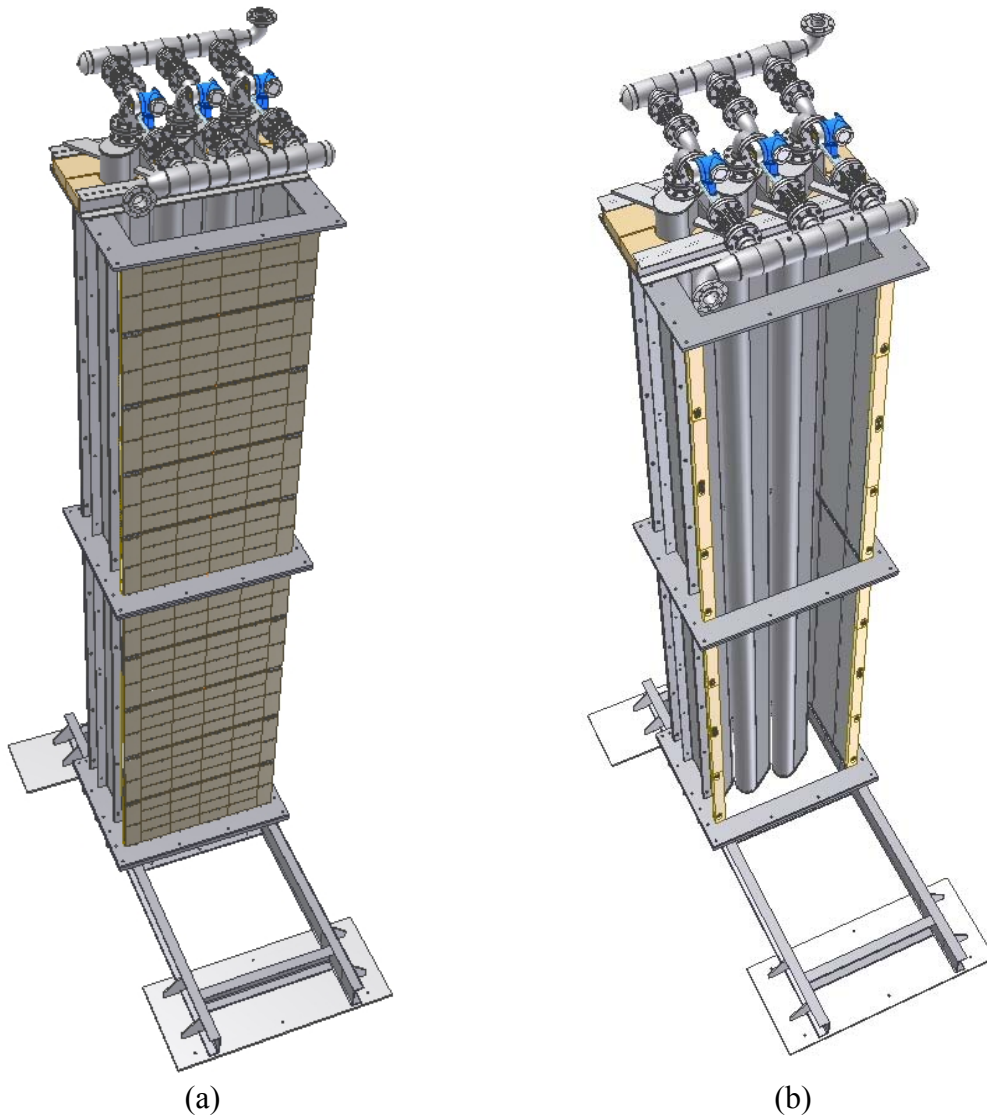


Figure 4.3. Cross Section of Test Assembly Showing Principal Details.



**Figure 4.4. Cavity Support Framework Modified for Variable Width Capability:
(a) with heater plates in place, and (b) with plates removed for clarity.**

water-based designs should the need arise in the future. Furthermore, this change would provide the possibility to conduct large, open cavity natural convection experiments at Rayleigh numbers that have not been addressed in the literature.

A rendering that illustrates the mechanical approach by which the support framework will be modified so that the cavity width can be varied is provided in Figure 4.4. The test section base plate support flange, as well as the flanges on the top and bottom of the support frames, will be replaced with new flanges that are opened up to the full cavity width of 102.9 cm. The vertical elements between the flanges that form the primary supports for the plates are 25.4 cm wide by 10.1 cm deep U-channels. For each section, the channels that hold the non-heated cavity walls will be fixed in place by welding these elements to the flanges. However, the channels that hold the heated wall plates will be attached to the end flanges by bolts that pass through filler panels that are welded across the end of channel. This will allow the channel width to be varied if the need arises during the course of the program.

As shown in Figure 4.3, the top flange of the upper heated section will also be modified to receive a support stand for the three standpipes. A blank-off plate that is machined to allow the standpipes to pass through is also provided beneath the support stand. This plate serves two purposes: i) it seals off the air space around the standpipes at the top of the test section, thereby creating a stagnant air environment that is consistent with the PBMR design, and ii) it provides a deck for the installation of insulation (10 cm thick) to minimize heat losses out of the top of the structure.

The standpipes are suspended (hung) from the support stand that sets on top of the test section. A second blank-off plate that is also machined to allow the standpipes to pass through is used to ensure proper positioning of the pipes within the opening at the bottom of the lower heated section inlet. This plate also seals the bottom of the test section to produce the proper boundary condition for the RCCS standpipe enclosure. Both blank-off plates are not rigidly attached to the plates so that the system can accommodate thermal expansion of the standpipes during the tests.

Aside from the electro-mechanical modifications to the system to mock up the water standpipes in the proximity of the reactor vessel, the scaling analysis² indicates that the facility should conserve flow areas and pressure drops in the balance of the system that interfaces with the header tank and chiller, particularly for the passive operational mode tests. Loop pressure drop can easily be adjusted using orifices placed between mating flanges in the flow circuit piping. In terms of conserving flow areas, the approach is to use similar piping diameter (i.e., 10 cm [4 inch] Schedule 40) to that employed in the prototype. In the prototype, this pipe size is used to feed four standpipes that are headered together, as opposed to the three headered standpipes that have been adopted for this experiment design. Thus, the flow area of the pipe feeding the array of standpipes is ~ 30 % larger for the experiment in comparison to the prototype. However, this is the closest match that can be obtained using standard schedule pipe. Moreover, the pressure drop across the larger diameter pipe used in the experiment can easily be increased using orifices. The header tank (which will be mounted on the original NSTF fan loft platform) is planned to be of similar diameter to the prototype, although the design details of that system are not known at this time.

The setup for the normal mode operating tests is shown schematically in Figure 4.5. The overall layout physically replicates the key elements of the PBMR RCCS design. A centrifugal pump (450 kg/min capacity) draws coolant from a 10 cm flanged fitting on the side of the header tank. An in-line throttle valve is used to adjust the loop total flowrate to the desired value (e.g., water flowrate to each standpipe under normal operating conditions is ~ 110 kg/min in the PBMR design, and so the total loop flowrate is ~ 330 kg/min for the three standpipe test setup). The coolant then passes through a high capacity (108 kW) chiller with feedback control that maintains the water supply temperature to the standpipes at a specified level. Note that a chiller is used in this application to simulate the ultimate heat sink in the PBMR RCCS. A refrigerant system is needed to reject the input heat while maintaining the inlet and outlet coolant temperatures of the standpipe at the required levels at full power conditions.

After the coolant passes through the chiller, the flow is headered into the three individual standpipes. In line flowmeters are used to measure coolant mass flowrate so that the flow split is known and accurate energy balance calculations can be performed. The water then exits the standpipes at the top where it is headered into the return line that passes the coolant to the top of the header tank. This completes the flow circuit for normal operations.

For passive operational mode tests, the system setup will be essentially the same as for the full power tests, with the following exceptions: i) the coriolis flow meters that are used to measure coolant flowrate to each standpipe will be removed to conserve the full supply line flow area to each standpipe,^a and ii) the supply line from the chiller will be isolated so that water will be passively drawn from lines located at the bottom of the header tank. The system setup for this stage of testing is shown in Figure 4.6. Two lines are provided. The first is a large (10 cm) diameter line to investigate situations when the pressure drop across the passive supply line segment is consistent with the balance of the system piping. A second line is also provided that can be orificed to examine situations in which the passive line has a higher pressure drop relative to the balance of the system. During passive operational testing, water flows by natural convection from the supply tank through one of these lines to the standpipes, and returns through the normal pathway to the top of the tanks. After the water reaches saturation and boiling commences, steam will pass through the top of the tanks and be vented to atmosphere. In the experiment system shown in Figure 4.6, a steam condensation and collection system is included to quantify the boiling rate, thereby providing additional validation data. In addition, the return line is instrumented with differential pressure transducers to characterize the extent of void formation due to flashing as coolant returns to the header tank.

Finally, the onset and extent of boiling within the system is influenced by the local saturation temperature. Given that the system is $\sim 1/2$ scale in height, then the saturation

^aThe ID of the flowmeter pipe segment is 1.9 cm. Thus, if left in the line, these units would produce a significant pressure drop relative to an open 10 cm diameter line that feeds each standpipe. However, note that this small diameter is required since virtually every type of commercially available flowmeter is set up for a flow velocity in the range of 0.6 to 3.0 m/sec through the measurement section. For the 1.9 cm diameter pipe, the flow velocity lies at the lower end of this range at the full power water flowrate of 110 kg/min to each standpipe.

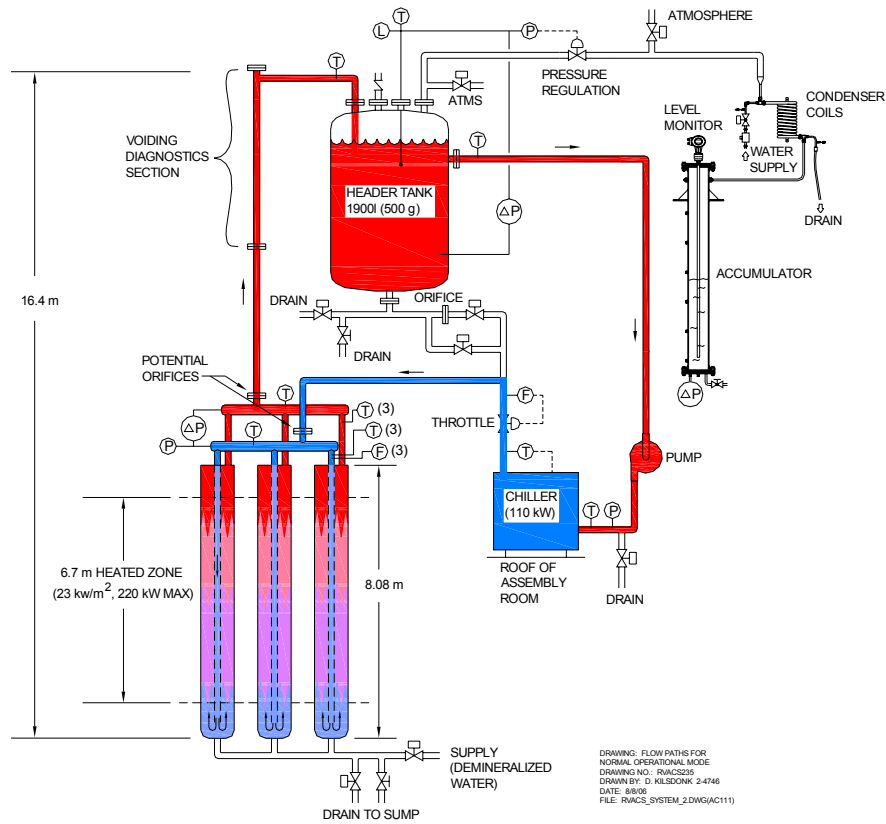


Figure 4.5. System Setup for Normal Mode Operational Tests.

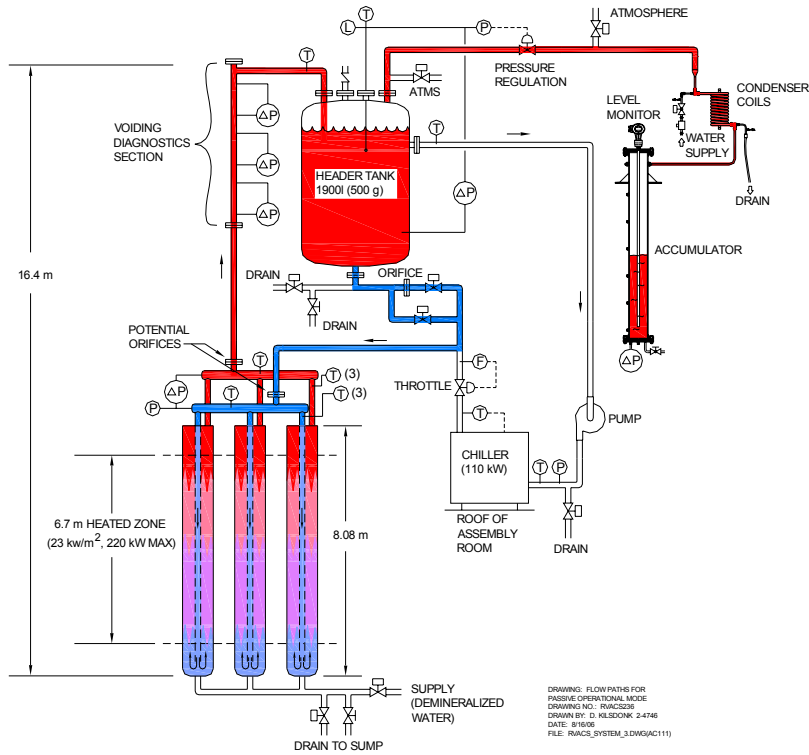


Figure 4.6. System Setup for Passive Mode Operational Tests.

temperature in the standpipes may be reduced by as much as 20 °C due to the differences in hydrostatic head between the experiment and prototype. On this basis, the system also includes a pressure regulator valve on the outlet to the header tank so that the system pressure can be raised to achieve prototypic absolute pressure within the standpipes if the need arises.

4.3 Heater Control System

The heater power control system consists of 20 independent control units, two for each of the 10 equally spaced axial heating zones that make up the 6.7 m long heated test section length (see Table 2.1). The heating elements in each axial zone are broken down into a main heating bank that is intended to simulate the thermal conditions on the exterior of the reactor vessel, as well as an exterior bank of heaters that are provided to compensate for heat losses at the outer edges of the test section. A photograph showing a typical panel that contains the heaters for one of the axial heating zones prior to installation on the test section was provided earlier in Figure 2.6, while the heater wiring and control circuitry are shown in Figure 4.7. As these figures indicate, each main heater bank is comprised of 4 parallel banks of centrally located heaters, each of which has four 1.1 kW heaters wired in series. Thus, each main bank consists of 16 heaters with a combined heating capacity 17.6 kW. The exterior heater bank that compensates for edge losses consists of four 1.1 kW heaters that are also wired in series. Thus, each 67 cm long axial heating zone has a collective heating capacity of 22.0 kW, yielding a total heating capacity of 220 kW for the 6.7 m test section length.

The main heater banks are controlled by Eurotherm model TE10P power controllers rated for 50 A. The banks of guard heaters are controlled by smaller Eurotherm controllers rated for 16 A. For experiments in which power regulation is needed, the power level of each heating bank is set at the console and relayed to the controller via a low level current signal from the SCXI chassis. These units are able to control power within $\pm 1\%$ of full scale during moderate variations in line voltage, load impedance, and ambient temperature. Each controller delivers an output signal proportional to actual power delivered to the heaters. The power is determined by current and voltage measurements made within the controller itself and accuracy is $\pm 1\%$ of measured power.

The control scheme for the heater banks can be configured to provide temperature regulation rather than power regulation. For this configuration, the control signals from the SCXI chassis are, on an external panel, switched over to the PID controllers. Heating power is then controlled by current signals from the temperature regulators rather than from the console via the SCXI chassis. Each PID (proportional, integral, derivative) controller has one thermocouple input and so each bank is regulated using a single representative heater temperature. The system is operated by selecting a temperature set point for the PID controller, which then automatically sends a current signal to increase (or decrease) power to raise (or lower) the temperature towards the set point. This configuration retains the power controllers' ability to measure actual delivered power and to send a representative current signal to the DAS.

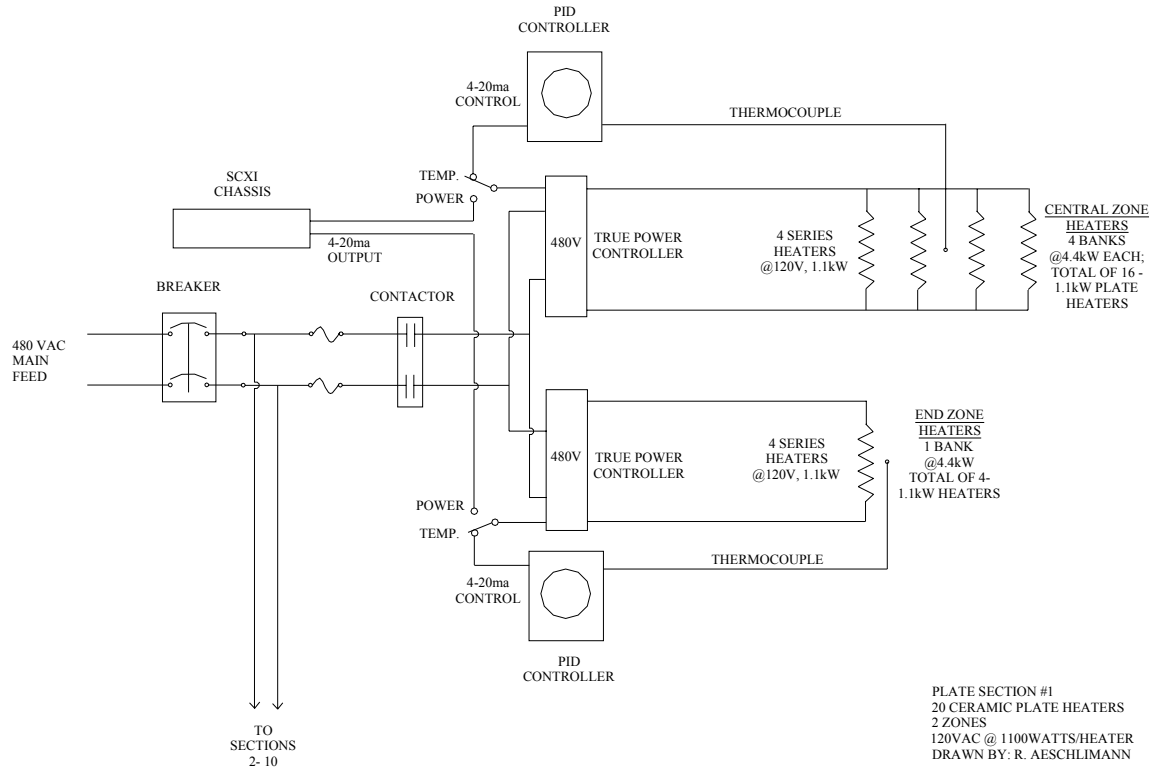


Figure 4.7. Heater Power Control System.

4.4 Data Acquisition and Control

All data acquisition and process control tasks will be managed by a PC executing LabVIEW under a Windows operating environment. The computer is linked to an SCXI chassis (National Instruments) that holds modules for signal conditioning, analogue to digital conversion, and switching. The chassis holds a 16-bit analogue to digital converter (ADC) with a maximum sampling rate of 200 kS/s and ability to multiplex up to 352 input channels. The unit has an input signal range of ± 10 V. The ADC module controls the signal conditioning and switching modules within the chassis. The chassis will be located near the test section to minimize the length of instrument cabling and control signal noise. A USB port on the ADC module provides a digital link between the chassis and the computer within the control room. Figure 4.8 provides a schematic of the layout for the data acquisition hardware.

Instrument output signals are connected to one of six SCXI-1102C signal conditioning modules. Each module has 32 input channels and provides cold-junction compensation for thermocouples. Each channel has a programmable gain amplifier and low-pass filter with a cutoff frequency of 10 kHz. For 4-20 mA signals, load resistors across the terminal block inputs are used to convert the current output to a voltage signal for the ADC. The input signal range for the SCXI-1102C is ± 10 V. These modules are used for signal outputs from flow meters, pressure transmitters, level sensors, heat flux meters, and heater power levels transmitted from the power controllers.

The power controllers for the plate heaters are regulated either through PID controllers, for temperature regulation, or through control signals from the data acquisition system for power regulation. The control signals are 4-20 mA current outputs from SCXI-1124 modules linked directly to the power controllers. Each module contains six channels and so four modules are needed to control all twenty banks of heaters. When the heaters are power regulated, they can be adjusted from the control room via a LabVIEW process diagram. For temperature control, the PID controllers outside the control room must be adjusted by hand.

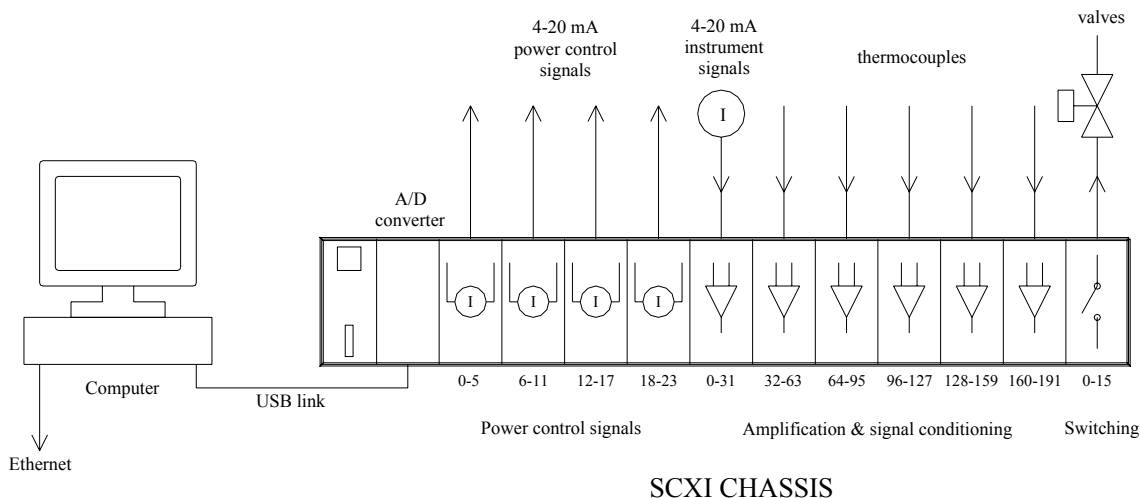


Figure 4.8. Data Acquisition and Control Systems.

A selected number of electrical devices will be controlled from the console using relay switches operated by LabVIEW. The relay modules have 16 SPDT electromechanical relays that can switch up to 2 A at 250 VAC. They are controlled by clicking on switches located on the LabVIEW process diagram. The relays are latched and so they maintain their state when the SCXI chassis is switched off or if there is loss of power in the control room. This system is used to control the positions of valves on the inlet lines to the standpipes and on the storage tank refill line.

4.5 Instrumentation

The approach for satisfying key water-based RCCS data needs is summarized in Table 4.1. In general, instrumentation for the facility is configured to characterize heat transfer rates between the water-filled standpipes and the plate elements representing the reactor vessel. The majority of the instruments are dedicated to measuring and/or controlling the state of the heaters and standpipes. Auxiliary instrumentation is used to monitor secondary parameters such as the level and pressure of the storage tank, the state of the system heat sink, and pressure heads pertinent to operation with natural circulation. Table 4.2 provides a summary of the instrumentation layout for the tests.

As is evident from Table 4.1, one of the most important requirements is to obtain data on the standpipe and cavity wall axial and radial temperature distributions under properly scaled test conditions. As shown in Figures 2.8 and 2.9, both the heated and unheated cavity walls of the

test section are highly instrumented to measure surface temperature distributions. By virtue of the heater power control system (see Section 4.3), the heat flux distribution on the heated wall will also be known. Finally, the test section is heavily insulated, so the unheated cavity wall will essentially be adiabatic.

Aside from the cavity walls, accurate knowledge of the RCCS standpipe surface temperature distributions is also important, since this information feeds directly into the evaluation of the local heat transfer coefficients, which is key information for code verification and validation. An illustration that shows the number and location of standpipe instrumentation is provided in Figure 4.9. As is evident, the central standpipe will be extensively instrumented to measure both the inner and outer surface temperatures on surfaces facing both the heated and unheated cavity walls. In addition, multi-junction thermocouple assemblies are used to measure axial water temperature distributions in both the downcomer and annular return regions of the standpipe. Furthermore, a minimum of 12 heat flux meters will be installed to provide local measurements of heat flux through the pipe walls. These instruments are attached to the inside of the standpipes to minimize any disturbances in the local heat flux. Heat transfer to the outer surface of the standpipes is via radiation and natural convection, which is more easily disturbed by the presence of a sensor than the forced convection or boiling heat transfer that takes place inside the standpipes. The heat flux data, in conjunction with surface and bulk water temperature measurements, will provide the necessary information for evaluating radial and axial heat transfer coefficient variations within the standpipe.

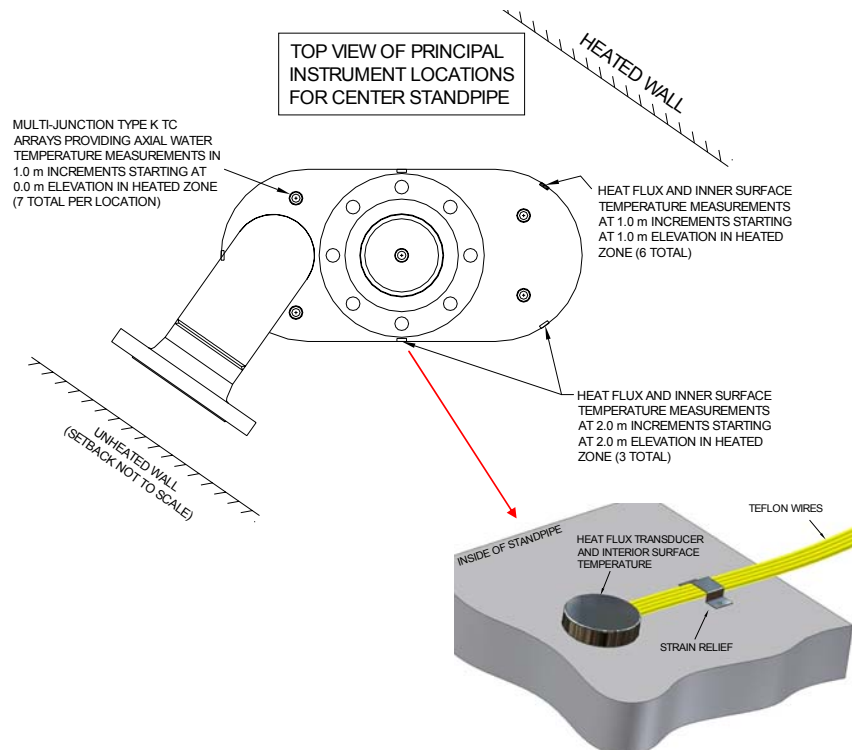


Figure 4.9. Center Standpipe Instrumentation Layout.

As shown in Table 4.1, another key data requirement is to obtain data on the emissivity and the bulk gas velocity and temperature distributions under properly scaled test conditions. In terms of the velocity and temperature measurements, the planned approach is to utilize insertable

hot wire anemometers with co-located, radiation-shielded, thermocouples to measure bulk gas velocity and gas temperature distributions at two axial positions along the heated cavity length. However, reputable vendors for these types of probes (e.g., Dantec) have indicated that the large temperature gradient across the cavity (e.g., a few hundred °C) may introduce large measurement uncertainties in the gas velocity measurements. Although it may be possible to develop a temperature compensation system for these probes, it is not clear at the current time that anemometry will work for measuring velocity distributions within the cavity. Thus, the backup instrument for this measurement is an insertable Pitot-static tube with a co-located, radiation-shielded thermocouple for measurement of the bulk gas temperature distribution. In terms of measuring cavity emissivities, viewports will be provided to measure the emissivity of the central standpipe exterior surface at two axial elevations when the system is at operating conditions.

As shown in Table 4.1, the fourth data requirement is to obtain data on the nature and extent of voiding within the return piping run from the standpipes to the header tank. Differential pressure transducers will be mounted at various locations along the pipe in order to measure local void fractions using well-known techniques. Finally, the onset and extent of boiling within the system is influenced by the local saturation temperature. Given that the system is $\sim 1/2$ scale in height, then the saturation temperature in the standpipes will be reduced significantly relative to the prototype due to the reduced hydrostatic head for the experiment. As noted earlier, the system is equipped with a pressure regulator on the outlet to the header tank so that pressure in the standpipes can be adjusted to match the prototype if the need arises.

In addition to the the instruments that are intended to provide detailed data on the heat transfer behavior within the RCCS standpipes and surrounding structure, other instruments will be provided to measure overall system performance and to carry out heat balances to verify that the system and equipment are functioning properly. For tests that are intended to investigate performance under normal forced flow conditions, thermocouples and resistance temperature detectors (RTDs) will be used to measure temperature rise across the standpipes, as well as temperature loss across the chiller that serves as the ultimate heat sink. Key instrument locations and system setup for the normal operating mode tests are shown in Figure 4.6. Note that it is important to use RTDs and specially calibrated thermocouples for coolant temperature measurements since the temperature rise across the system is only a few °C during normal operations. This difference can be compared with the measurement uncertainty of $\pm 2.2^\circ\text{C}$ for a standard Type K thermocouple. Thus, the measurement uncertainty is about as large as the expected coolant temperature rise, which provides the rationale for requiring precision temperature measurement instruments.

Aside from the temperature measurements, overall water flowrate through the system, as well as flowrate through each individual standpipe, will be measured. This information, as well as the input power to the heaters and the temperature changes measured across the standpipes and chiller, will allow energy balance checks to be performed, and to evaluate overall system thermodynamic performance.

Instrument locations and system setup for the passive mode tests are shown in Figure 4.7. As is evident, for these tests the chiller is isolated and the water supply flowpath is through the

orificed supply line located at the bottom of the header tank to the standpipes, whereas the return line is the same as that used for normal operations. In this case, basically all the same measurements will be made as for the full power case, but data gathering will be augmented by collecting and condensing steam that passes through the header tank after saturated conditions are reached, and void fraction distribution along the return line will also be determined. This additional information will help quantify system performance during passive system operation, and augment the database for code validation.

Table 4.2. NSTF Instrumentation Summary for Water-Based RCCS Testing.

Instrument	Manufacturer	Units	Range	Accuracy	Purpose/Location
Heat flux meter	International Thermal Instrument Co.	12+	0-10 kW/m ²	± 5%	Heat flux meters mounted inside stand pipes on side facing heated wall.
Thermocouples (Type K)	Claud S. Gordon	175+	0-1250°C	±2.2°C	Surface temperature measurement on heated and unheated cavity walls
Thermocouples (Type K)	ARI Industries	50+	0-1250°C	±0.1°C	Pipe surface and water temperature distributions throughout system. (each junction specialty calibrated to reduce uncertainty)
RTD	ARI Industries	4	0-1000°C	±0.05 °C	Precision measurement of water temperature rise across standpipes
Power controllers	Eurotherm Controls	20	0-20 kW	± 0.2 kW	Both controls and measures power to plate heaters.
Coriolis flow meter	Endress + Hauser	3	0-240 kg/min	± 0.5%	Inlet water flowrate to each stand pipe for normal operating tests
Turbine flow meter	Omega	1	0-700 kg/min	± 5% FS	Loop flowrate for normal operating tests
Level meter	Krohne	1	0-2 m	± 3 mm	Header tank water level
Emissivity	Mikron Model MQ1300	2	0-1	± 3 °C	Standpipe outer surface emissivity at operating conditions
Pressure transmitter	Rosemount	2	0-10 bar	± 1%	Supply and storage tank pressures.
ΔP	Rosemount	1	0-60 kPa	± 60 Pa	Redundant level measurement in storage header tank
ΔP	Rosemount	4	0-10 kPa	± 10 Pa	Void distribution measurement in return line to header tank

5.0 COST AND SCHEDULE FOR FACILITY MODIFICATIONS

In the previous sections of this report, an overall high-level plan has been developed for mechanical, electrical, instrumentation, data acquisition, and control system modifications to NSTF in order to supply the data needed to qualify both CFD and system-level codes for application to the water-based RCCS under both normal and passive operational modes. The purpose of this section is to provide a cost and schedule for carrying out this work. These estimates factor in the design and planning work that has already been accomplished and documented in this report. Note that these estimates are laboratory related; i.e., they do not cover companion code validation and analysis activities that will be carried out in parallel with, and in support of, this work. Cost and schedule estimates for the analysis tasks are documented elsewhere.

A summary of key tasks associated with carrying out this scope of work is provided in Table 5.1, along with a timeline for completion of each task. For reference, an outline of the overall workscope that provides additional details is provided in Appendix A.

Task 0: This task is for the development of an Experiment Requirements Document (ERD) that will define the key data and operational needs for the tests. Although this document is to be developed by the sponsors at no cost to the project, it is nonetheless shown in the schedule since it is a key element that drives the mechanical and instrumentation designs for the experiments. Although a conceptual design for water-based RCCS testing within NSTF has been developed and documented through this report, the design cannot be finalized until the specific end-user experiment requirements are documented.

Task 1: In terms of project activity, the first task is to obtain the necessary laboratory Environmental, Safety, and Health (ES&H) approvals to initiate the work. This includes preparation and submittal of National Environmental Protection Act (NEPA) documentation, as well as a safety plan that covers the laboratory work. The key deliverables from this task are DOE and laboratory approvals to initiate testing in the facility.

Task 2: This task consists of preparation of a Quality Assurance (QA) plan for the program. This plan will be developed in close collaboration with the sponsor to ensure that the results produced by the project will meet the end-user needs and requirements. The key deliverable from this stage of the work will be a Program QA Plan that is approved by the sponsor, laboratory, and project management.

Task 3: This task consists of finalizing the facility conceptual test plan per the ERD developed as part of Task 0 of this project. The finalized test plan will cover: i) the mechanical design and layout, ii) instrumentation, data acquisition, and power control systems, and iii) the test operating procedures. This work will include finalizing the fabrication drawings, as well as the specifications that are required for procurement. The planning covers the testing to validation RCCS performance under both normal full power operations, as well as passive off-normal conditions. The particular bounding accident sequence to be evaluated in the facility will be specified by the sponsor in the ERD, but may include the Depressurized Loss of Forced Convection (DLOFC) cooling transient. From the mechanical viewpoint, this includes the fabrication of the instrumented water standpipes, standpipe support and bracing structures within

Table 5.1. Schedule for Completion of Key Tasks.

No.	Task	Time from Project Initiation																							
		Year 1												Year 2											
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0	Sponsor Develops Experiment Requirements Document																								
1	Obtain ES&H Approvals to Initiate Laboratory Work		—	—	—	◆																			
2	Develop Program QA Plan		—	◆																					
3	Develop Facility Test Plan		—	—	—	◆																			
4	Develop Test Matrix			—	—	—	—	—	◆																
5	Prepare Test Area		—	—	◆																				
6	Acquire Key Equipment and Services for Facility Modifications		—	—	—	—	—	—	—	—	—	—	—	◆											
7	Prepare Test Facility				—	—	—	—	—	—	—	—	—	—	—	—	—	—	◆						
8	Conduct Facility Shakedown Testing															—	—	—	—	◆					
9	Initiate Testing According to Task 4 Plan																				—	—	—	—	◆

NSTF, header tank(s), interconnecting piping, and heat sink. The instrumentation plan for measuring flowrates, temperatures, pressures, and surface emissivities at key locations throughout the system will be finalized. Design and specifications for the electrical system for controlling and monitoring of the cavity wall heaters will also be completed. Finally, general operating procedures for the facility will be developed, from cold shakedown testing to hot startup. The key deliverable from this stage of the work will be an approved facility test plan for testing under both normal and off-normal operating conditions.

Task 4: This task covers the key area of experiment planning. Laboratory personnel will collaborate with analysts and data end-users to identify key RCCS conditions and data ranges expected during both normal and passive operating conditions. Based on this input, a test matrix and test operating procedures will be developed that will generate the data needed to support model development and code validation. The key deliverable from this stage of the work will be an experiment test matrix planning report.

The balance of the tasks shown in Table 5.1 cover the laboratory efforts required to bring the facility up to an operational stage and to begin the conduct of tests identified under Task 4. Progress during these various stages of work will be documented in the form of monthly progress reports to the sponsor.

Task 5: This effort covers preparation of the laboratory space where the facility resides. The high bay area will be cleaned and surplus items will be disposed of. The lighting in the upper loft area will be upgraded to facilitate the work. The lab space will be painted and made to look presentable. Ladders and flooring will be brought up to current OSHA standards. Similar cleaning and repair activities will be conducted in the facility control room.

Tasks 6: Once the lab space is updated, modifications to the facility will be initiated. A key element of this task will be the procurement of services and equipment that are required to conduct the work; details are provided in subsection 6 in Appendix A.

Tasks 7a: This effort covers generic mechanical preparations to the facility that will be required independent of the RCCS coolant type (i.e., air vs. water) or detailed vendor design. In particular, this step covers modification of the test section base weldment and cavity wall support framework to allow the cavity width to be adjusted so that different RCCS designs can be accommodated without significant facility rework. In addition, this change would provide the possibility to conduct large, open cavity natural convection experiments at Rayleigh numbers that have not been addressed in the literature. Key steps involved in this stage of the facility mechanical modifications consist of:

- a) disassembly and storage of NSTF components above the heated test section length,
- b) removal and storage of the existing (30 cm) inlet plenum,
- c) disassembly of the facility down to the base weldment,
- d) removal of insulation from the two heated test sections to facilitate work,
- e) rework of the flanged cavity support framework to accommodate wider flow cavity geometries (up to ~103 cm) that will be required to mock up the PBMR RCCS,
- f) machining of the plates to receive new instruments for flow and temperature characterization within the standpipes and surrounding cavity, and
- g) rewiring the heater power feeds and the associated heater power control and monitoring instruments into the DAS.

Task 7b: Once a particular RCCS design has been selected for investigation in NSTF, this effort covers the balance of the facility electromechanical modifications that are required to investigate RCCS performance for a specified vendor design. For the PBMR RCCS, these steps consist of:

- a) manufacture of instrumented water standpipes,
- b) installation of the pipes in the modified test assembly, and
- c) fabrication and assembly of the balance of the system, including header tank(s), chiller, and interconnected piping.

With these final steps completed, miscellaneous instruments will be installed and wired into the Data Acquisition System (DAS) according to the Test Plan.

Task 8: After the facility is fabricated and assembled, shakedown testing will be initiated. This work will include checkout of the controllers and heaters, pumps, and flowmeters for proper operations under initially cold and then low-power conditions (heater temperatures < 150 °C). After these steps are completed, the facility will be brought up to conduct initial low power testing (heater temperatures ~150 °C) to verify proper integral operation.

Task 9: With these steps completed, actual data generation will be initiated according to the test matrix developed under Task 4 of the overall workscope.

A summary of the overall costs associated with carrying out this work is provided in Table 5.2. In terms of staff, the project is assumed to consist of a Principal Investigator who is in charge of the overseeing the overall workscope, reporting, and for developing the project documentation shown in Tasks 1-4. The PI is assumed to be covered at a level of 50 % on the project during the first year of the project when the development of a considerable amount of program documentation is required, and 25 % during the second year when the documentation requirements are reduced. In addition, there will be a Lead Experimenter who is in charge of overall laboratory activities. The Lead Experimenter must be covered at a level of at least 75% on this project. In addition, two Test Engineers are required to carry out the workscope: one in charge of the mechanical systems, and the other in charge of electrical/instrumentation systems. Both Test Engineers are assumed to be covered at a level of 75 % on the project. Thus, the overall staff effort required to carry out the work is estimated to be ~ 2.75 Full Time Equivalents (FTEs) during the first year, and ~ 2.50 FTEs during the second year. Aside from staff, laboratory technicians are needed at a level equivalent to 1.5 FTEs during the first year and 1.0 FTEs during the second year.

Table 5.2. Estimated Costs for the Proposed Workscope.

Project Year	Staff Effort		Tech Effort		M&S (K\$)	Total (K\$)
	FTE	Cost (K\$)	FTE	Cost (K\$)		
1	2.75	700	1.5	324	256.0	1274
2	2.50	780	1.0	250	100.0	1130
Total		1605		590	356.0	2410

The effort rates shown in Table 5.2 are based on those within the Nuclear Engineering (NE) division at ANL. The rates are those projected for FY07-08 based on current rates within the division assuming a 4% rate of inflation. Aside from effort, Materials and Services (M&S) are required to carry out the work at the levels shown in Table 5.2. These estimates include all laboratory overhead and taxes.

The total cost to modify the facility and to begin generating validation testing of the water-based RCCS is estimated as 2410 K\$. Of this total estimate, the estimate for conducting shakedown testing and performing experiments for the first six month period after startup is included as ~ 550 K\$. Note that the costs for a number of items are design dependent and therefore preliminary since the exact scale and details of the experiment design must first be finalized following completion of Task 0 of this overall workscope.

6.0 SUMMARY AND CONCLUSIONS

An engineering plan for mechanical and instrumentation modifications to the Natural Convection Shutdown Heat Removal Test Facility (NSTF) at Argonne National Laboratory has been developed to meet key VHTR water-based RCCS data needs. The specific objectives of the experiment planning process were as follows:

1. provide CFD and system-level code development and validation data for the water-based RCCS under properly scaled test conditions for both normal and passive (i.e., natural convection) flow conditions, and
2. support RCCS design validation and optimization activities.

Companion scaling and scoping analysis activities² carried out to support the experiment planning indicate that: (a) strong 3-D effects in the RCCS result in large heat flux, temperature, and heat transfer variations around the tube wall; (b) there is a large difference in the heat transfer coefficient predicted by turbulence models and heat transfer correlations, which underscores the need for experimental work to validate the thermal performance of the RCCS; and (c) tests at the NSTF would embody all important fluid flow and heat transfer phenomena in the water-based RCCS, in addition to covering the entire parameter ranges that characterize these phenomena.

7.0 REFERENCES

1. M. T. Farmer, D. J. Kilsdonk, C. P. Tzanos, S. Lomperski, R. W. Aeschlimann, and D. Pointer, "Natural Convection Shutdown Heat Removal Test Facility (NSTF) Evaluation for Generating Additional Reactor Cavity Cooling System (RCCS) Data," ANL-Gen IV-058, September, 2005.
2. C. P. Tzanos and M. T. Farmer, "NSTF Feasibility Study for VHTR Water-Cooled RCCS Experiments," ANL-Gen IV-079, September 2006.
3. C. P. Tzanos, "CFD Analysis for the Applicability of the Natural Convection Shutdown Heat Removal Test Facility (NSTF) for the Simulation of the VHTR RCCS," ANL-Gen IV-055, September 2005.

APPENDIX A

NSTF FACILITY MODIFICATION PLAN FOR WATER-BASED RCCS

1. Obtain Laboratory and DOE ES&H Approvals:

- a. Prepare and submit National Environmental Protection Act (NEPA) documentation.
- b. Prepare and submit Laboratory Activity Data Document (LADD) and safety plan for Experiment Review Committee (ERC) review and approval.

Deliverable(s): DOE/ANL approvals to initiate laboratory work

2. QA Program Plan

- a. Work collaboratively with INL and vendor to develop a QA program plan

Deliverable(s): QA program plan

3. Facility Test Plan

- a. Finalize mechanical plan and supporting fabrication drawings for modifying NSTF to accommodate water-based RCCS testing, including widening of the test cavity, fabrication of the instrumented water standpipes, standpipe support and bracing structures within NSTF, standpipe inlet and return manifolds, header tank(s), interconnecting piping, and heat sink.
- b. Finalize instrumentation plan for measuring flowrates, temperatures, pressures, and surface emissivities at key locations throughout the system.
- c. Finalize electrical plan for operation, control, and monitoring of cavity wall heaters.
- d. Develop detailed data acquisition and control strategy.
- e. Develop general operating procedures (cold shakedown testing and hot startup) for both normal and passive operational mode tests.

Deliverable(s): Final facility test plan report

4. Experiment Planning

- a. Collaborate with analysts and data end-users at INL, ANL, and the vendor to identify key RCCS conditions and data ranges expected during both normal and passive operational modes for potential VHTR water-RCCS designs.
- b. Develop a test matrix and companion facility operating procedures that will generate the data needed for code validation.

Deliverable(s): Experiment test matrix planning report

5. Test Area Preparations:

Deliverable(s): Progress on test area preparations described below will be documented in the form of monthly progress reports to the sponsor.

- a. High bay area:

- i. Remove and dispose of old equipment and surplus insulation from loft.
 - ii. Clean area thoroughly.
 - iii. Replace light bulbs in upper structure and have double-headed spot lights installed on railing to increase lighting level.
 - iv. Paint walls and structures as appropriate.
 - v. Have ladders and balcony flooring brought up to OHSA standards (covered by PFS).
 - vi. Fix exterior wall insulation that is falling down in the upper areas of the bay.
- b. Control room:
- i. Remove and store RF generator
 - ii. Remove existing floor tile
 - iii. Clean area thoroughly
 - iv. Paint walls and ceiling
 - v. Install new floor tile
 - vi. Have roof checked for leaks and patched accordingly by PFS

6. Manufacture/Acquire Key Equipment and Services for Facility Modification

- a. Machine Shop Services (196 K\$)
- i. Instrumented and dummy RCCS standpipes (30 K\$).
 - ii. Standpipe I-Beam support structure, top cover plates (5 K\$).
 - iii. Standpipe inlet and exit manifolds, bellows, flanges (15 K\$).
 - iv. Bottom section cover plate and hardware (2 K\$)
 - v. Machine upper and lower unheated cavity walls to receive instruments (anemometers and/or pitot tubes, emissivity meters, and vertical lifting lug attachments) (8 K\$)
 - vi. Machine upper and lower heated cavity walls (vertical lifting lug attachments) (4 K\$)
 - vii. Modify base weldment and the upper and lower cavity wall support frameworks for variable cavity width capability from 30 to 120 cm widths. (20 K\$)
 - viii. Header tank (ASME Section VIII) (10 K\$)
 - ix. Worchester pressure control valve for controlling header tank ambient pressure (5 K\$)
 - x. Condenser coil for header tank outlet (1 K\$)

- xi. Supply and return piping from standpipes to heat sink and header tank, 4 inch Schedule 40 piping and ANSI Class 150 flanges; manufactured to ASME B31.3. (25 K\$)
- xii. Procure 108 kW chiller for system heat sink, and install on roof of assembly room adjacent to NSTF high bay (70 K\$)
- xiii. 100 gpm water pump (1 K\$)
- b. Instrumentation (105 K\$)
 - i. Thermocouples for instrumenting standpipe walls with specialty three-point calibrations for each junction (100 units) (10 K\$).
 - ii. Multi-junction thermocouple arrays for measuring standpipe axial water temperature distributions on supply and annular return sides of the standpipe, including specialty three-point calibrations for each junction (6 units with 7 junctions each) (14 K\$)
 - iii. Heat flux meters (18 @ 0.4 K\$ ea. = 7 K\$)
 - iv. Pressure transducers (Rosemount; 10 @ 2 K\$/ea. = 20 K\$)
 - v. Anemometers for air cavity transverse velocity/temperature measurements (4 @ 2 K\$ ea. = 8 K\$)
 - vi. Traversing system for anemometers (8 K\$)
 - vii. Bench top NIST-traceable reference for anemometer calibration (10 K\$)
 - viii. PID controllers for heater temperature control (10 K\$)
 - ix. Coriolis flow meters (3 @ 5K\$ ea. = 15 K\$)
 - x. Turbine flow meter (1 K\$)
 - xi. Header tank level meter (2 K\$)
- c. Data Acquisition and Control (32.5 K\$)
 - i. Dedicated PC and screens for DAQ (4 K\$).
 - ii. DAQ cards, Multiplexers, SCXI chassis, switch modules (300 Channel capacity) (21 K\$)
 - iii. Dedicated LABView license for facility; professional version (2.5 K\$)
 - iv. Equipment console (3 bay) (5 K\$)
- d. Heater Power Control System (43 K\$)
 - i. Heater wall power controllers (Eurotherm, 20 @ 1.5 K\$ ea. = 30 K\$)
 - ii. PID temperature controllers (20 @ 0.5 K\$ = 10 K\$)
 - iii. Relay Racks (3 K\$)

- e. Miscellaneous (61 K\$)
 - i. Waste disposal (3 K\$)
 - ii. Electrical (lighting & electric power services) (5 K\$)
 - iii. Painting services (8 K\$)
 - iv. Insulation removal/disposal (WMO) (15 K\$)
 - v. Scaffolding/lift for routine work on test assembly (20 K\$)
 - vi. Insulation for facility (10 K\$)

7. Test Facility Preparations:

Deliverable(s): Progress on facility preparations described below will be documented in the form of monthly progress reports to the sponsor.

- a. Disassemble transition ductwork from fan loft to the top of the upper heated section and archive components for potential future use in air-based RCCS tests.
- b. Remove and archive the existing (12”) inlet plenum for potential future use.
- c. Prepare the heated test section for water-based RCCS testing as follows;
 - i. Label and roll back thermocouples to plate walls for both upper and lower heated test section components.
 - ii. Disassembly upper and lower heated test section components (as two pieces) and move these components (by ANL rigging services) to Bldg. 206 high bay for reworking.
 - iii. Once the parts are received, remove insulation from both sections (WMO contract).
 - iv. Remove both the cavity wall plates from the support frames for the top and bottom sections, and then archive the frames for potential future use.
 - v. Machine the wall plates for new instrumentation penetrations, and also add lifting lugs so that the plates can be moved once the test section is vertically assembled.
 - vi. Once machining is complete, check continuity and resistance for plate heaters and verify that the panel mechanical attachments are still in good shape. Also check thermocouples for proper operation and installation. Make repairs as needed.
 - vii. Reattach the plates to the new adjustable cavity wall support frames after the frames are received from shops. Then have the reworked test section components moved (by ANL rigging services) back to the NSTF test bay.
 - viii. Once the parts are received, re-insulate the components and then assemble on the test stand.

- d. Prepare the standpipes for installation as follows:
 - i. After the half-segments are received from shops, install and pot surface temperature thermocouples, and install and solder down heat flux meters on the center highly-instrumented standpipe.
 - ii. Weld together $\frac{1}{2}$ segments to obtain bulk standpipe material
 - iii. Weld in top and bottom end-caps to complete the pipes.
 - iv. Seal instrument leads using gland seals through the bottom flange of the center highly instrumented standpipe.
- e. Install RCCS tube simulators in NSTF:
 - i. Install top blank-off plate that is cut to receive the standpipes, as well as standpipe support I-Beam structure, on top of the upper test section.
 - ii. Install the bottom blank-off plate that is cut to receive the standpipes at the bottom of the test section.
 - iii. Using the high-bay crane, lower the three standpipes into position on the support stand. Bolt the standpipes down to the support framework at the top; the pipes float at the bottom.
- f. Header tank and inter-connecting piping:
 - i. Install header tank on the fan loft balcony using the cell crane.
 - ii. Install supply and return headers to standpipes (set up initially for normal operational tests, with Coriolis flowmeters in-line to each standpipe).
 - iii. Install balance of system piping connecting header tank to heat sink and supply/return headers in test section.
- g. Chiller heat sink:
 - i. Have PFS/engineering investigate maximum roof loading for assembly room next to NSTF high bay; add shoring as needed to receive 108 kW chiller.
 - ii. Have electrical service brought to roof to power the chiller (480 3- Φ 70 A service)
- h. Heater power controllers:
 - i. Install and wire up heater power and temperature controllers, and wire these units into the DAQ switching chassis.
 - ii. Rewire power feeds from the control room into the relay racks in the high bay.
- i. Instrumentation-Install instruments according to the test plan in the various locations and wire the instruments into the DAQ.

8. Conduct Facility Shakedown Testing.

Deliverable(s): Progress on shakedown testing will be documented in the form of monthly progress reports to the sponsor.

- a. Conduct cold shakedown testing of flow loop that simulates normal power operations to verify proper functioning of loop pump, valves, flowmeters, and other instrumentation.
- b. Checkout controllers, heaters, and instruments for proper operations under low-power conditions (i.e., heated wall temperature $< 150\text{ }^{\circ}\text{C}$) to verify proper integral operation for both normal and passive system operating modes.
- c. Conduct initial low power testing (heater temperatures $\sim 150\text{ }^{\circ}\text{C}$) to verify proper facility integral operation.

9. Initiate Testing According to Plan Developed Under Step 4.0.



Nuclear Engineering Division

Argonne National Laboratory
9700 South Cass Avenue, Bldg. 208
Argonne, IL 60439-4842

www.anl.gov



UChicago ►
Argonne_{LLC}



A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC